SNS Diagnostics†

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Abstract. The Spallation Neutron Source (SNS) Project is a collaborative effort to build the next generation neutron science facility at Oak Ridge, TN. The facility will deliver a 2 MW proton beam to a liquid mercury target. Neutrons from this target will be moderated and sent to several state-of-the-art instruments. Six national laboratories are involved in SNS construction. Berkeley (LBNL) will build the front end that produces a 2.5 MeV, 52 mA H- beam. Los Alamos (LANL) is responsible for the 1 GeV linac with a superconducting section provided by Thomas Jefferson (Jlab). Brookhaven (BNL) is building the transfer lines and accumulator ring. Oak Ridge (ORNL) and Argonne (ANL) have responsibility for the target and instruments. All activities are coordinated by SNS project office at Oak Ridge. The high beam power, a desired availability of 95%, and an aggressive commissioning schedule lead to some interesting challenges in beam diagnostics.

THE SPALLATION NEUTRON SOURCE[1,2]

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Neutron Science

Neutron scattering is a valuable tool for exploring the properties of materials. Because they possess a magnetic moment but no net charge, neutrons form highly penetrating probes of magnetic structure. Properly moderated, thermal neutrons can excite molecular vibrations in solids. Scattering experiments can resolve structural information from about 10^{-13} to 10^{-4} cm. Isotope substitution can be exploited by replacing hydrogen with deuterium in selected molecules.

Figure 1 depicts the evolution of neutron sources. The pulsed sources allow time of flight techniques. Accelerator based sources tend to be more environmentally acceptable than reactors while providing the most intense pulsed neutron beams available. After commissioning at Oak Ridge in 2006, the SNS will be the most intense source in the world.

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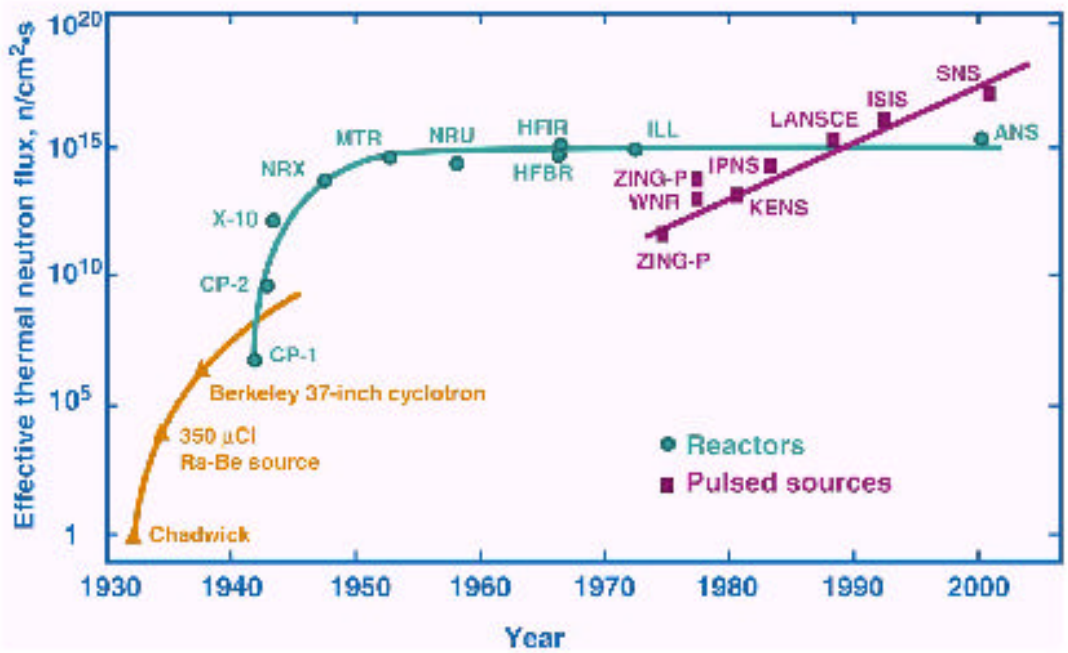

FIGURE 1. Evolution of neutron sources.

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SNS Partnership

SNS is currently the largest accelerator project in the United States. It is also the most extensive collaboration ever put forth to construct a DOE facility. As shown in Figure 2, the collaboration is a partnership of six laboratories:

- Lawrence Berkeley National Laboratory (LBNL)
- Los Alamos National Laboratory (LANL)
- Brookhaven National Laboratory (BNL)
- Thomas Jefferson National Accelerator Facility (JLab)
- Oak Ridge National Laboratory (ORNL)
- Argonne National Laboratory (ANL)

The Front End (called the Ion Source in the figure) is designed and built by LBNL. It contains an ion source, a low energy beam transport line (LEBT), RFQ, rebunching cavities, and the medium energy beam transport line (MEBT). LANL is responsible for the physics design of the linac and construction of the warm sections including the drift tube linac (DTL) and the coupled cavity linac (CCL). JLab will deliver the superconducting RF (SRF) cavities and associated cryogenic system that form the final section of the linac. BNL designs and builds the high energy beam transport line (HEBT), the accumulator ring, and the ring to beam target line (RTBT). ORNL is building the liquid mercury target. Argonne and ORNL are responsible for the neutron

instruments. All design, construction, installation, and commissioning activities are coordinated by the SNS project office located in Oak Ridge.

FIGURE 2. The SNS partnership and site layout.

Facility Overview

Referring again to Figure 2, the beam can be followed from the ion source to the Spallation target. The ion source produces a 65 mA H- beam that is extracted at 65 kV with a macropulse length of 1 ms. An electrostatic LEBT matches this beam into the RFQ and also chops it into <700 ns minipulses with gaps of about 250 ns. After acceleration to 2.5 MeV in the RFQ, a traveling wave chopper cleans up the minipulses in the MEBT. The MEBT also contains rebunching cavities and quads to match the beam into the DTL. The DTL and the RFQ are both 402.5 MHz structures. Handoff from the DTL to the CCL occurs at 87 MeV. The CCL then accelerates this beam to 185 MeV where the SRF linac takes over and accelerates the beam to a full energy of about 1 GeV. Both the CCL structures and the niobium cavities in the SRF section operate at 805 MHz.

A switch magnet sends beam to either a 33 kW linac tuning dump or into the HEBT. When the tuning dump is used, the linac operates in a low power mode of reduced rep rate or shortened macropulse length. The HEBT transports the H- beam to the ring where a carbon injection foil strips the H- to protons. This charge changing injection process is about 95% efficient, so that at full power, over 100 kW of neutral

TABLE 1. SNS Parameter List.

Parameter	Value
Proton beam power on target	2.0 MW
Average proton beam current on target	2.0 mA
Proton energy on target	~1.0 GeV
Pulse repetition rate	60 Hz
Peak linac H- current	52 mA
Chopper beam-on duty factor	68 %
Front-end and linac length	332 m
DTL output energy	87 MeV
CCL output energy	185 MeV
SRF linac output beam energy	~1.0 GeV
Linac beam duty factor	6.0 %
HEBT length	170 m
Accumulator ring circumference	248.0 m
Ring orbit rotation time	945 ns
Number of injected turns	1060
Ring fill time	1.0 ms
Ring beam extraction gap	250 ns
RTBT length	151 m
Protons per pulse on target	2.08E+14
Proton pulse width on target	695 ns
Target material	Hg
Number of neutron beam shutters	18
Initial number of instruments	10
Availability	95% (goal)

hydrogen is stripped by a secondary foil and transported to the 200 kW injection dump.

The ring accumulates approximately 1000 turns via a transverse painting process. An h=1 primary RF system augmented by a higher harmonic system attempts to keep the pulse uniform and keep the gap clear for extraction. Through the chopping process (in the front end) and the accumulation process, allowable current in the gap is only 10^{-4} of the accumulated macropulse current. If this requirement is met, extraction can be clean enough to allow hands on maintenance in that area.

After extraction, the RTBT transports the 695 ns pulse to the target. Phase advance between the multi-module extraction kicker and the target is a multiple of pi/2. This allows the beam to land centered on the target even if a kicker module failure results in reduced extraction angle. The target itself is composed of flowing mercury in a stainless steel vessel. The mercury can handle the 2 MW beam power and due to its high atomic number, is a prolific source of neutrons. These neutrons are moderated down to thermal energies and initially delivered to 10 different instruments. More instruments and possibly a second target station will be added after the facility operates.

The primary parameters of the SNS facility are summarized in Table 1. Figure 3 depicts the beam structure that is measured by diagnostics in the linac. Beam induced signals in the ring are similar to those in the linac, but the current increases by an order of magnitude during the 1 ms accumulation time. Due to the beam's momentum spread and the ring's momentum compaction factor, linac microstructure is very weak in the ring. During full power operation, the beam in the RTBT line is simply a 695 ns pulse containing $2 \cdot 10^{14}$ protons.

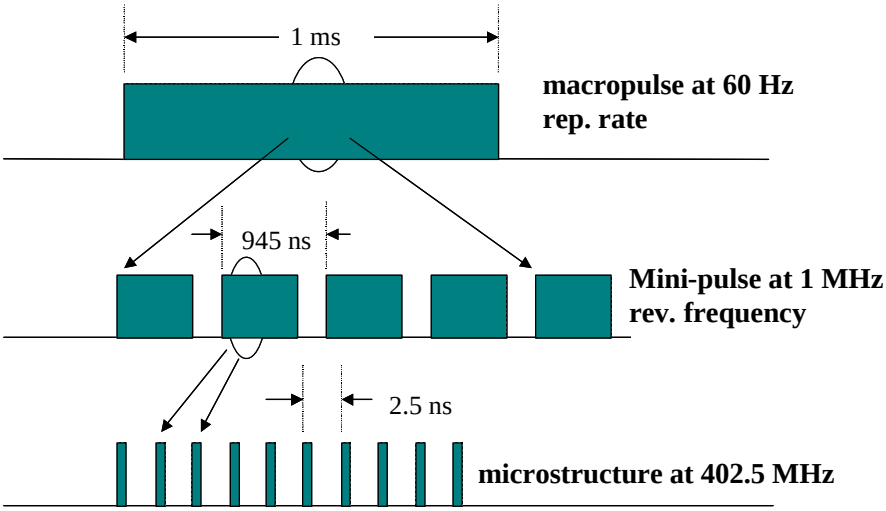

FIGURE 3. Beam structure.

BEAM DIAGNOSTICS

Diagnostics Layout

The quantities of all permanently installed diagnostics as well at their locations are itemized in Table 2. In addition, a well-instrumented diagnostics station will be provided temporarily as the linac is commissioned. Figures 4 through 6 depict the layout of systems in the transfer lines and the ring.

TABLE 2. List of diagnostics for each section of accelerator.

System	Subsys.	Lab	MEBT	DTL	CCL	SRF	HEBT	Ring	RTBT
BPM & Phase	Pickups	LBL	6						
	Pickups	LANL		12	16	30	2		
	Pickups	BNL					20	44	17
	HF Elec.	LANL	6	12	16	30	22		
	LF Elec.	BNL						44	17
Loss	System	BNL		12	24	58	40	119	57
Current	Pickups	LBL	2						
	Pickups	LANL		6	2	3			
	Pickups	BNL					5	2	5
	Elec.	BNL	2	6	2	3	5	2	5
Wires	Pickups	LBL	5						
	Pickups	LANL		6	8	29			
	Pickups	BNL					11	1	5
	Elec.	LBL	5						
	Elec.	BNL		6	8	29			
	Elec.	BNL					11	1	5
Harps	Pickups	LANL		2			2		2
	Elec.	LANL		2			2		2
Misc. Profile	Gas Fluor.	LANL							
	Foil Video, etc	BNL						1	
Beam-in-Gap	Laser	LANL					1		
	kicker	BNL						1	
Emitt.	System	LBL	1						
	System	LANL							
Phase Width	System	LANL					1		
Ion Profile	System	BNL						1	
Tune	System	BNL						1	

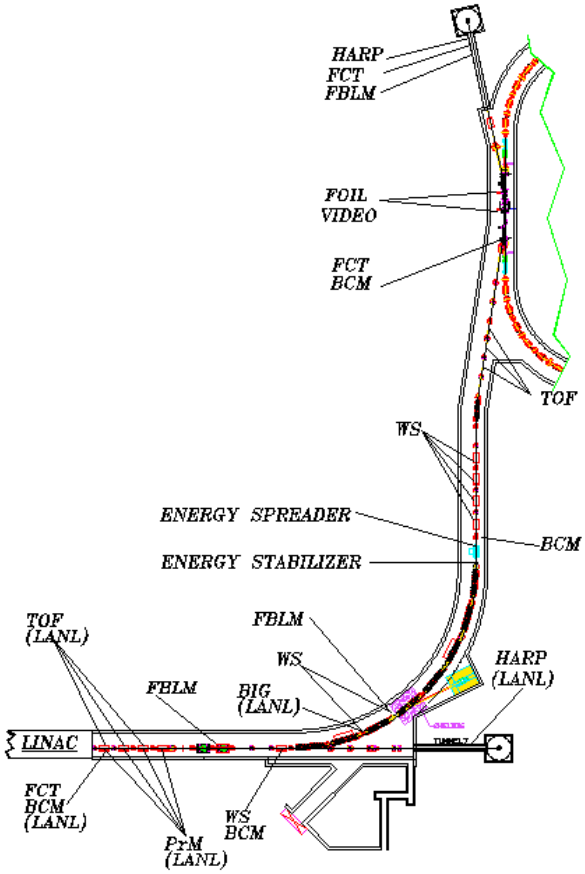

FIGURE 4. Diagnostics layout in the high energy beam transport (HEBT) line.

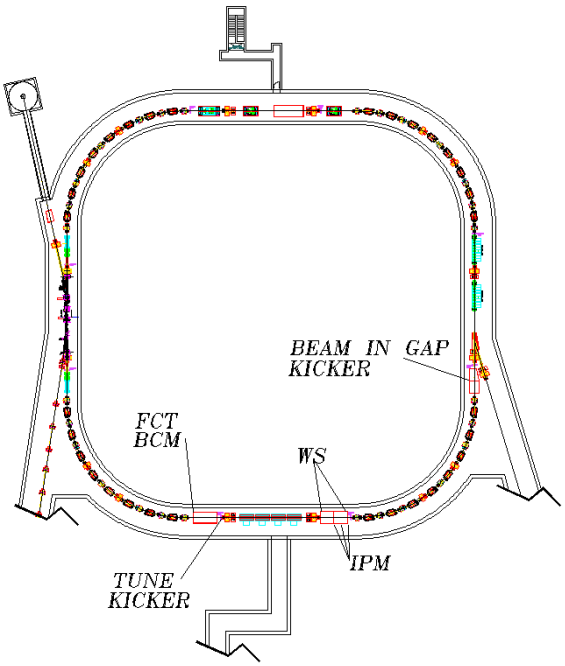

FIGURE 5. Diagnostics layout in the Accumulator Ring.

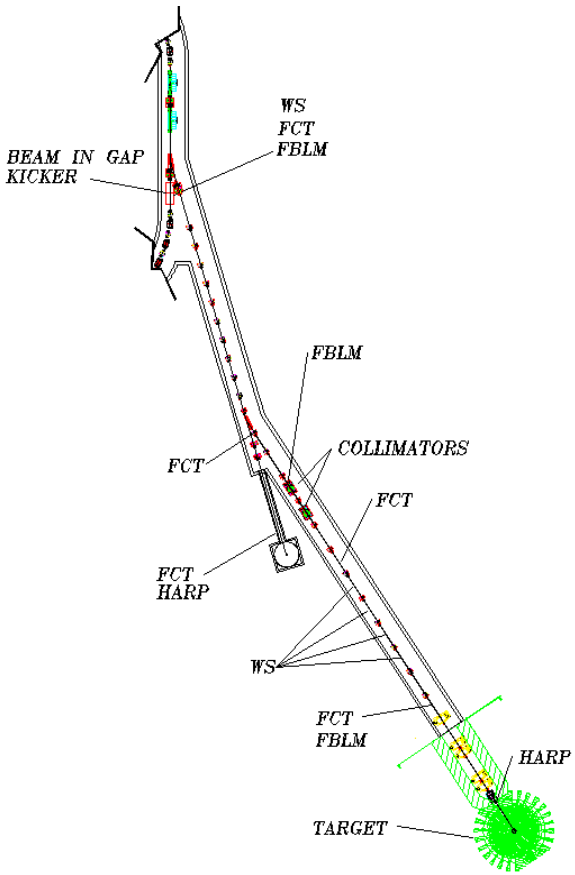

FIGURE 4. Diagnostics layout in the Ring to Beam Target (RTBT) line.

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Diagnostic Systems

Several of the diagnostics systems are explained in more detail below. Additional information on the linac diagnostics is available in a paper at this conference[3].

Position and Phase Monitors

All beam position monitors in the SNS will be 4-electrode, 50-ohm striplines. Therefore, all locations will report both vertical and horizontal position and will allow the test signals to be injected into the orthogonal plane. With this technique, an online calibration can be performed that relies only on the mechanical stability of the electrode itself and provides an end-to-end signal integrity check.

In the MEBT, Linac, and HEBT, the pickups will also be used as phase probes. The length of these electrodes is appropriate for 402.5 or 805 MHz operation depending on location. They are a single port shorted design that is mechanically simple and allows location within a quad where space is tight. In the DTL, the electrodes are mounted

within the drift tubes. In this case, the 805 MHz harmonic will be used to avoid strong interference at the 402.5 MHz fundamental. Likewise, near the 805 MHz CCL and SRF structures, the 402.5 MHz signal will be used.

In the ring, the primary orbit measurement will be made at baseband. The ring and RTBT stripline are left open to allow flexibility in tailoring the transfer impedance. This might be advantageous someday if a stronger low frequency signal is desired. The electrode length also allows coupling to the high frequency linac microstructure. By discriminating between the orbit of the circulating charge and a freshly injected minipulse, the space charge depressed tune might be observed.

The baseline design of the high frequency (HF) position electronics incorporates log amplifiers for wide dynamic range and simple normalization. For phase measurement, I-Q detection of the sum signal is proposed. An alternative technique that uses I-Q detection on all four signals is under investigation. By allowing a full vector calibration, this design avoids the requirement of phase matched signal cables. The 50 MHz IF would be sampled at 40 MHz to acquire the I-Q data stream.

The ring BPM electronics design has progressed through a basic block diagram concept to the evaluation of components and circuits. The basic design concept has focused on a base-band scheme that would maintain a linear system through the digitizer section. This allows linear methods to balance channels and operate on the signals. The present concept will use two 7.1MHz – matched - 5 pole Bessel filters to both shape and provide anti-aliasing filtering for a 65MSPS digitizer. The filters and amplifiers will provide in excess of 84db attenuation at 32.5MHz providing a 14 bit conversion accuracy with a 5MHz bandwidth. The use of two signal paths permits gain changes with no loss in turn-to-turn data. External attenuators are expected to be necessary to accommodate the large signal levels expected during accumulation. Minimum loss pads are presently being considered to match the probe cables to the filters and calibration switching system. These pads will also reduce the signal level that is expected to be high enough to maintain less than 1mm resolution even at the first turn. Test circuit boards are being prepared to investigate switches, amplifiers, filters and digitizers for this application.

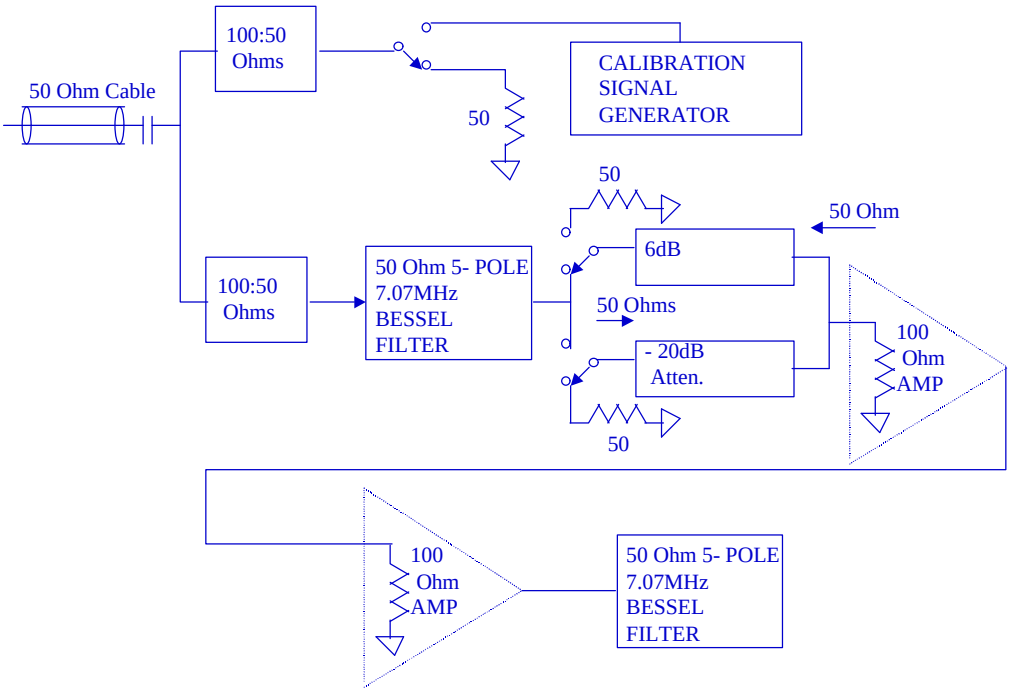

FIGURE 5. BPM Prototype Analog-Front-End Block Diagram.

Loss Monitors

The very high intensity of the SNS will make the BLM system the primary diagnostic tool for tuning and preventing excessive activation and equipment damage. As the primary diagnostic tool there must be sufficient detector coverage in all sections of the SNS. For many years the AGS accelerator complex has used extended ion chambers made from hollow large diameter coaxial cables to assure complete spatial coverage. These "line" detectors also offer the advantage of 1/r spatial dependence rather than the $1/r^2$ of point detectors. However, their length prevents them from being placed close to the beam line, lowering their sensitivity, and mechanical considerations preclude high bias voltage, limiting their linear range. For these reasons smaller volume sealed glass ion chambers were used in RHIC and will be used in SNS. To obtain uniform coverage similar to that of the long coaxial cable ion chambers, many more detectors are required. Detectors will be placed at essentially every quadrupole, where the beta-max occurs, and at other key points. In addition there will be a number of other detectors which can be moved to points for temporary use. Because the ion chambers will have about 1 μsec rise time they will not be able to see losses within the bunch, so scintillator-photomultipliers will be installed at Ring injection and extraction, and other strategic points. The system must be able to observe low losses over prolonged periods as well as fast high losses from faults. This is in addition to the 10^3 range during accumulation in the Ring. Quenching of the super-conducting cavities in the Linac can occur from a rapid local loss. To prevent excessive activation, the Linac, transfer lines and Ring are all limited to a 1 W/m loss over a 1 second duration. This is equivalent to a loss of 10^{-4} of the full intensity per pulse summed over the entire Ring.

A beam inhibit system will be implemented in hardware using a programmable threshold detector and will shut off the beam at the Front End for the remainder of the pulse within 5-10 μsec. In addition, for each detector a 1-second moving sum will be computed and compared against the 1 W/m limit. Beam inhibit will be done in higher level code and used to warn the operators. In the Ring the sum must include all detectors in the array.

About 300 (Linac 94, HEBT 45, Ring 96, RTBT 57) sealed, argon-filled glass ion chambers will be used as the primary detectors for monitoring beam losses. The basic ion chamber[4] was originally designed by R. Shafer at FNAL in 1982 for the Tevatron. This design was also used in the RHIC with modifications to improve radiation hardness and break a ground loop. Sensitivity of the ion chamber is 70 nC/Rad or 19.1 pA/Rad/hr .

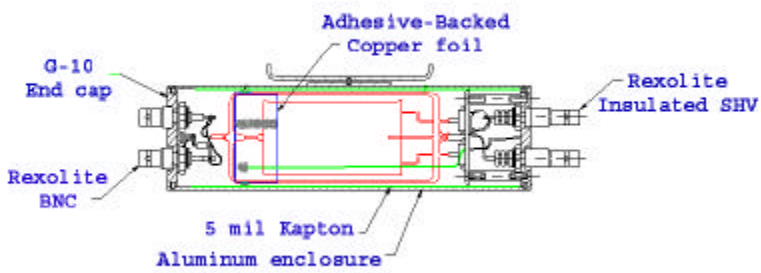

FIGURE 6. Ion Chamber Assembly.

Scintillator-photomultipliers (SPMs) will be located in critical areas around the ring such as injection, extraction, collimators, downstream end of each straight section, and in the transfer lines. They are intended to give data about clipping of the bunch ends or losses due to beam in the gap and losses due to instabilities if they occur. They will not be used as the detectors in the global loss monitoring. Liquid cell scintillator will be used because of increased radiation hardness. The leakage of the liquid scintillator raised safety concerns. The use of these detectors[5] at Fermilab was discontinued due to the difficultly and cost of mixed waste disposal. The improved design of Bicron ™ detectors[6] is hoped to eliminate these problems. Typical detector response is on the order of 100 micro-Coulombs per Rad.

Circuitry for the ion chamber BLM system has not yet been designed but will take advantage of the fast electron signal to provide rapid interrupt in the case of high beam losses. In the Ring and RTBT at least one gain change will be required.

While the standard 60 Msa/s, 14-bit digitizer would seem to be overkill for such low bandwidth signals the advantage of signal averaging may warrant its use.

Programmable threshold detectors will be included to provide rapid sensing of excessive beam loss and allow turn off of the beam within 5-10 μsec.

The SPMs will be buffered and viewed by the standard 60 Msa/s digitizers for general acquisition, allowing 50-60 samples during the micro-bunch. They will also go to a wideband multiplexer to allow acquisition on one of the 1 GSa/s scopes for more detailed viewing.

Current Monitors

The current monitoring system has progressed to a design that will minimize the number of different sensors required. The basic current monitor will be a Bergoz® Fast Current Transformer "FCT". This monitor is capable of following the fast edges of the chopped beam, and will provide 0.25 V/A into a 50 Ohm load. It can provide a droop of less than 0.1% per microsecond. This transformer is ideal for observing the character of the current on a mini-pulse basis, however, to observe the 1ms long macro-pulse droop compensation circuitry will be required. The basic concept is to digitize as soon as practical and process the signals digitally. Droop compensation together with base-line restoration can be provided using digital techniques. A variable gain amplifier is required in the Ring and RTBT to accommodate the large dynamic range of the accumulated beam signals. A dual amplifier path approach is under consideration to allow gain switching without losing a turn.

Under investigation are methods that will permit in-situ calibration of the system. Each FCT will include a secondary winding that could be used for calibration. One scheme would use a Bergoz® integrating current transformer "ICT" that is is not affected by high frequency magnetic losses to provide charge information for calibrating the FCTs. This transformer is also being considered for placement in the Ring to provide a charge reference.

Components for this system are similar in requirements to the BPM system and where possible common components will be used. Test circuit boards are being prepared to investigate switches, amplifiers, filters and digitizers for this application. The general concept is shown in the block diagram of Figure 9, and a functional block diagram is shown in Figure 10.

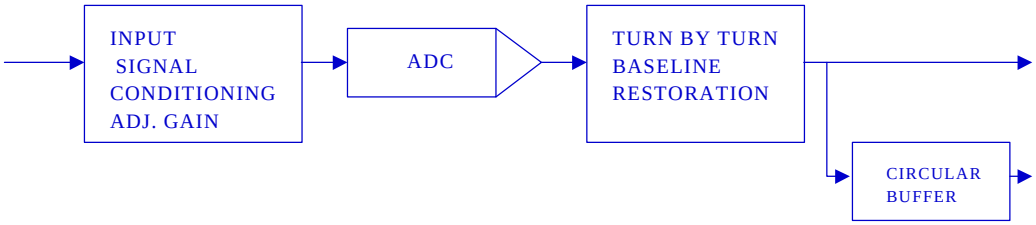

FIGURE 7. BCM General Signal Processing Concept.

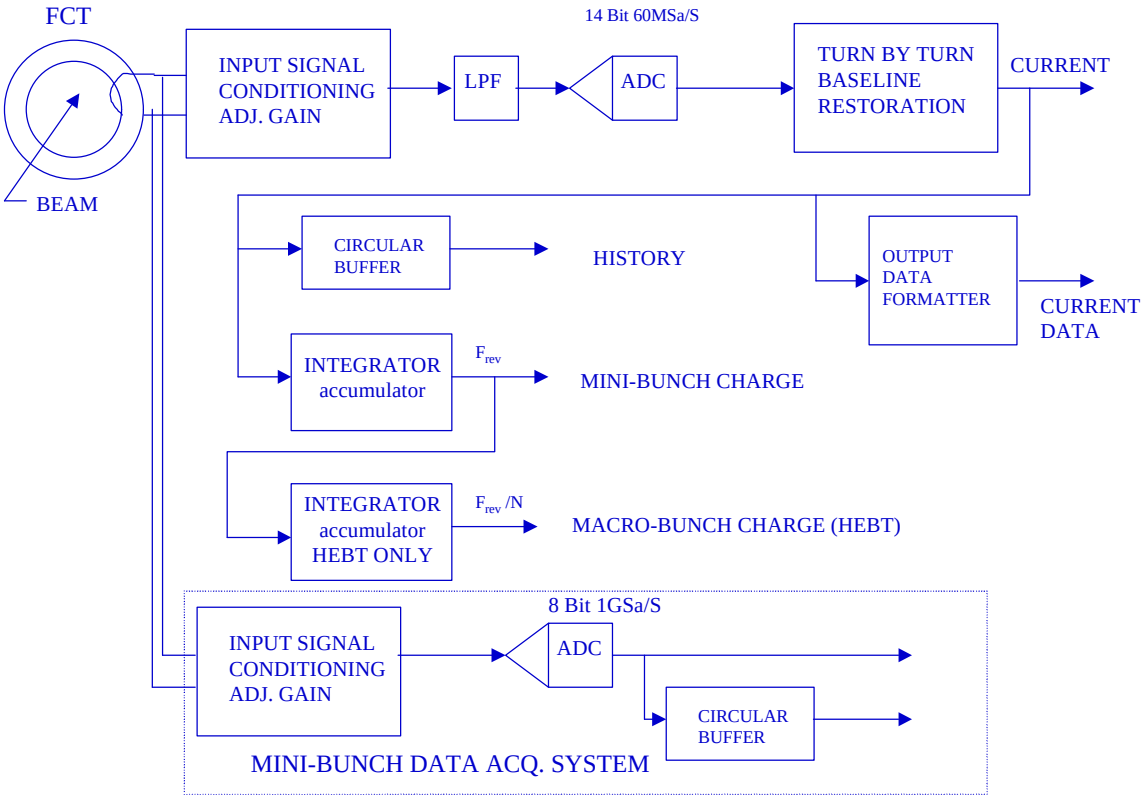

FIGURE 8. BCM Analog-Front-End Electronics Block Diagram.

Profile Monitors

A conservative choice of profile monitor was required to meet the commissioning schedule of the front end. Therefore, scanning wires have been selected as the baseline design. Other options are under development and are described below. At low energies, the beam stops in the wire. Therefore, current in the wire is measured directly. At higher energies, secondaries can be measured with fast loss monitors. To reduce design effort, all wire scanners should have a similar design with only slight application-specific variations. Cleanliness is a primary concern that may drive design choices in the SRF section.

Even at high beam energies, the wires typically will not survive a full macropulse. Therefore, two alternatives are under investigation. The gas fluorescence technique could be used at full beam power, but it has not been proven reliable for quantitative measurements of small beams. The work on LEDA at Los Alamos looks promising and may lead to techniques that are applicable to SNS. At BNL, tests will be performed with a laser-based device. This device neutralizes a thin slice of the H-

beam. The resulting change in transmitted beam might be measurable with current transformers or the losses might be measurable with the fast loss monitors. Multiple measurements with a scanning laser produces a profile measurement in a manner similar to that of a wire scanner.

Harps will be used to qualify each beam pulse that is sent to a dump or to the target. The target harps are the most critical and a redundant system is being considered. If the beam profile on the target is not within specifications, the target could prematurely fail. Therefore, a harp will monitor each pulse and provide a beam-enable signal to equipment protection system.

A video system will monitor the beam profile on the injection foil. At full power, the foil is only expected to last a few weeks. Therefore, this system will be used to detect the inevitable degradation and possibly the catastrophic failure of this foil.

To survive the intense beam in the ring, a residual gas ionization monitor will be used to monitor the changing profile. Electrons will collected in a magnetic field. This will avoid space charge effects while the mobility of electrons will allow turn by turn measurements. The hope is that the accumulation and painting process can be observed. Experience with a similar device in RHIC will be valuable for the SNS program.

Beam in Gap Measurement

Significant uncontrolled beam loss can occur due to beam in the extraction gap. It must be verified that the current in the 250 ns gap is 10^{-4} down from that of the main pulse. This difficult measurement will be performed in two ways.

One system will be located upstream of a HEBT dipole. A laser beam will be expanded to cover the transverse size of the H- beam. With appropriate timing of this Q-switched laser, a fraction of the H- in the gap will be neutralized. This neutral beam travels straight through the dipole and is detected outside the vacuum chamber. The current design specifies a Cerenkov detector for its speed and insensitivity to background.

The other system utilizes a transverse kicker in the ring combined with loss monitors near the betatron collimators. Due to the strength of affordable kickers, a complete measurement will require many turns. This system has the advantage of clearing the gap in a controlled way during the measurement

FUTURE

The SNS commissioning schedule is shown in Table 3. This aggressive plan will drive the priorities of the diagnostics team. In particular, the MEBT diagnostics must be available at Berkeley by Summer of 2001. Each lab has a role in this and each will feel the pressure as front end commissioning drives the project from concept to reality.

TABLE 3. Commissioning Plan

Activity	Start date
Commissioning Front End at LBL	Fall 2001
Beam Available for the DTL at Oak Ridge	Summer 2002
Beam Available for the CCL	Early 2004
Beam Available for the SC Linac	Summer 2004
Beam Available for the HEBT & RING	Fall 2004
Beam Available for the RTBT & TARGET	Spring 2005
Project Complete	Mid 2006

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LBNL: John Staples, Alex Ratti, Darryl Oschatz, …

SNS/ORNL: Richard Witkover, Sasha Aleksandrov, …

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