BNL-105618-2014-TECH

BNL/SNS Technical Note No. 049;BNL-105618-2014-IR

Considerations in Designing a beam-In-Gap Monitor for the Spallation Neutron Source

R. Witkover

September 1998

Collider Accelerator Department

Brookhaven National Laboratory

U.S. Department of Energy

USDOE Office of Science (SC)

Considerations in Designing a "Beam-In-Gap" Monitor for the Spallation Neutron Source

BNL/SNS TECHNICAL NOTE

NO. 049

R. Witkover

September 23, 1998

ALTERNATING GRADIENT SYNCHROTRON DEPARTMENT
BROOKHAVEN NATIONAL LABORATORY
UPTON, NEW YORK 11973

SNS Technical Note

Considerations in Designing a "Beam-In-Gap" Monitor for the Spallation Neutron Source

Richard Witkover

Background

The Spallation Neutron Source (SNS) will consist of a 1 GeV H-minus linac, producing an approximately 1-msec pulse at 60 Hz, feeding a 200-m circumference ring. The pre-bunched beam will be stripped to protons and accumulated over approximately 1000 turns and extracted in a single turn to the neutron production target transport line. The Ring RF system will keep the single bunch well confined during the cycle, resulting in an output pulse width of approximately 550 nsec. With a design intensity of 10^{14} per pulse, un-controlled losses must be kept to a level of 10^{-4} or less. One possible loss mechanism would be from beam which escapes from the bucket but stays in the machine in the gap between the ends of the bunch, and is lost at extraction. It would be desirable to have a detector in the SNS Ring to measure the beam in the gap (BIG) and aid in eliminating its source. Beam in the gap could also be present as it is delivered from the Linac and the MEBT chopper. A separate monitor must be located in the HEBT line to determine if the beam in gap is coming from the Linac and be used to correct the Linac. While a LASER based system would work well on the H-minus beam in the HEBT, the lack of an orbital electron on the circulating protons makes it impossible to use this technique in the Ring.

PSR BIG Techniques

The Proton Storage Ring (PSR) at Los Alamos National Laboratory is a predecessor of the SNS. While no specific detector is dedicated to measuring gap beam, Mike Plum has devised a way of observing it[1]. By timing the extraction kicker to fire just after the end of the bunch, rather than before its start, the beam in the gap is extracted first followed by the beam in the bunch. This timing is necessary because the current transformer observing the beam must be set at high gain for the gap signal and will deeply saturate during the main bunch due to the 3-4 order increase in magnitude. The results clearly show significant beam in the gap under certain operating conditions of the PSR.

While this is a very clever use of existing hardware. It is limited to a single measurement at extraction and provides no information about growth during the cycle. There are a number of problems in extending this technique to the SNS Ring. At the PSR the timing was shifted so that the kicker fired at the beginning of the gap, however, a corresponding portion of the tail would be lost in the ring, causing unacceptable radiation. If the kicker pulse length was simply extended to a full turn then during normal operation the gap beam would be extracted and lost on the rotating shutter or appear as a low level head or tail on the bunch. This might be acceptable since otherwise the gap-beam would be lost in the Ring or wiped across the kicker. Unfortunately the SNS kicker is designed with a 180 nsec rise time, which is far too slow for the approximately 250 nsec gap. With this rise time the gap beam would still be lost on the extraction components. Designing a kicker with a much faster rise time would represent a significant change of scope which has not been included in the schedule or cost estimates for the Ring Extraction Systems.

Other Kicker Techniques

Another approach would be to use a separate, fast rise time, small angle kicker to deflect only the gap-beam into a collimator where it could be observed with a fast gated loss monitor. An additional advantage would be that the gap-beam would be dumped in a controlled loss location. This approach could be implemented as either a resonant discharge magnetic kicker or as a multi-turn RF deflector such as the Damper.

With the Damper operating in an Anti-Damping mode, the gap-beam would be moved towards the collimator over a number of turns, gradually scraping the transverse distribution until the entire gap is cleared. An estimate was made using the AGS Damper as a model. This system uses a 500 W linear 200 MHz amplifier on each of the 1-meter long deflector plates. While there is no problem with achieving a 20 nsec rise time for the RF pulse, the weak deflection causes a slow buildup of the displacement amplitude, moving the beam onto the collimators over perhaps 100 or more turns, which is too long. An alternative would be to use a separate deflector with a more powerful pulser. Since linear response would not be needed, achieving an order of magnitude stronger kick should be practical. However, using the Damper, which is already included in the design, would be an advantage from both a cost and space point of view. Further study will be needed to determine the necessary RF power for specific lattice locations of kicker and collimator and to find a suitable non-linear RF pulser.

The other approach would be to use magnetic instead of electric deflection. The extraction kicker for the SNS Ring uses a thyratron discharged PFN to develop a 550 nsec pulse with a 180 nsec rise time. This kicker will deflect the beam across the full aperture of 150 mm. A similar design with rise time of 50 nsec or less would not be economically feasible, even with the smaller kick needed to wipe the beam on the collimator, but a resonant discharge kicker might be practical. A simple capacitor discharged through a fast switch into the kicker magnet inductance will produce a half-sine current pulse. This is far from linear during the gap duration. However, if the kicker is designed to produce twice the deflection needed to hit the collimator then the loss will occur at 50 nsec into the 250 nsec pulse. As long as the full kick still holds the beam on the collimator and the detector’s field of view uniformly covers the impact region then this approach will work. If a more uniform kick is required then a significant improvement can be had by firing two capacitor banks, each resonant at 150 nsec base width, with a delay of 100 nsec between the triggers. In this case if the threshold current is at 87% of peak then the rise time is still under 50 nsec but with only 13 % variation. Note that using the dual resonant discharge with twice the required current, the rise time becomes 25 nsec. Further study will be required to determine the kick requirements for the specific lattice location and to provide detailed cost estimates for the kickers.

Beam Current Transformer as a Monitor

Since the Beam Current Transformer (BCT) is a non-intercepting detector with a wide dynamic range it was considered as a possible BIG monitor. The transformer itself could be designed to avoid saturation over the more than 4-decades range but the electronics would require time dependent gain (gating) or limiting to tolerate the large signal difference. A possible circuit using a gated attenuator and variable gain amplifiers is shown in Figure 1. In this design the BCT was assumed to have 100 turns into a 1 Ohm local load. A GaAs RF switch (Mini-Circuits KSW-2-46), which has been measured to have 72 dB isolation , provides ($2.5x10^{-4}$) attenuation during the main bunch signal. The AD600's are 40 dB fixed gain current mode opamps with programmable input ladder attenuators. With an equivalent input noise of 1.4 nV/sqrt(Hz) and a cascaded gain of 80 dB, the signal to noise ratio at 10^{-4} of peak bunch signal is 5.34 with an output of 0.5 V for the gap signal. An alternate design using AD640 fast logarithmic amplifiers in cascade is also a possibility. In this case no RF switch is required since the log-amps are designed to saturate gracefully under the peak bunch input.

Since the BCT couples to the magnetic field of the beam current it will not have DC response and the signal baseline will shift over the 1 msec SNS Ring cycle until the area of the signal above and below the baseline are equal. The time constant for this is the L/R of the transformer. To be able to see a signal 3 orders of magnitude below the bunch signal, the baseline shift must be kept to 10^{-3} or less to prevent the electronics from saturating due to the baseline offset, which will require a 1-second L/R time constant for the transformer. At the other end of the bandwidth the transformer must have a rise time sufficiently fast to allow it to settle before the gap beam appears. For a circuit with a square pulse input to reach 99.9% (0.001) of its final value in 30 nano-sec the upper cut-off frequency must be 31.3 MHz. It will reach 99.99% (0.0001) in 41.7 nano-sec.

BCT's have been built with nano-second rise times and with multi-second decay times, however, achieving both in a single unit is not simple. One solution would be to use two transformers, one optimized for high and one for low frequency performance with a suitable cross-over between them. It may also be possible to build a single transformer to meet these requirements. To obtain long decay times the transformer must have many turns and use a massive core of high permeability material. On the other hand, fast rise times require few turns since the turn-to-turn capacitance resonates with the transformer inductances. Tapping the winding periodically with resistors connected to a circumferential ground wire can ameliorate this significantly. The choice of turn-spacing and resistor value is empirical. To investigate this approach a number of windings were made on cores a little smaller than required for SNS.

Tests on the damped transformers indicated that a 10 nano-sec rise time could be achieved but with considerable overshoot, some of which was due to impedance mismatch in the test fixture. A decay time-constant of 0.12 second was measured but this could be increased with a larger core. It is likely that more complete exploration of the parameters would result in less overshoot, however, achieving less than a few percent is expected to be difficult. This would be unacceptable since the trailing edge of the main bunch would then ring through the gap time with a magnitude obscuring the beam signal.

Discussions with M. Plum[2] (PSR) about a transformer built specifically to measure the gap beam indicated that the unit did not have a fast enough rise. Subsequent discussions with J. Bergoz[3] of Bergoz Inc., who built the PSR transformer under contract, indicated that while the bare transformer had a rise time of 1 nano-sec it had to be rolled-off to 5-10 MHz to reduce the overshoot to an acceptable level. Bergoz, who is perhaps the leading producer of BCT's in the world, was convinced that a transformer with the specification for SNS was not practical. Pearson Electronics, who also manufacture high quality BCTs, have not been approached with these specifications but might be interested in studying the design. While it may not be possible to build a transformer with sufficiently small overshoot for this bandwidth, it may be practical to use feedback to compensate for the ringing. Since the overshoot may be due to resonances in the winding or mismatch in the cabling, both of which are set by the physical configuration, it should be possible to measure this frequency and design a narrow band filter to isolate this component of the signal. If the output of this filter is fed into the input of the amplifier with the proper gain and phase then it may be possible to cancel the overshoot. Since the signal bandwidth of the transformer will also be set by this ringing frequency, some degradation of the rise time will occur, but can be minimized by keeping the filter width as narrow as possible. The appeal of a passive detector makes this approach still one to consider.

Wire Probe as BIG Monitor

A wire across the vacuum chamber intercepting the beam generates secondary emission electrons which could be used to monitor the time structure of the beam in the gap. Accelerating the secondary electrons and then deflecting them with the beam RF provides a synchronous measurable distribution of the beam longitudinal profile. This is the standard technique used in proton linacs to measure the longitudinal density distribution[4,5] , providing a bandwidth of 10's of GHz. Because the SNS Ring bunching frequency is several orders of magnitude below that of the Linac, GHz response is not required, and a much simpler device without the deflecting RF can be designed. Alternatively the need for external fields can be eliminated by detecting the radiation produced by the beam-wire interaction using a fast gated scintillator-photomultiplier, rather than detecting secondary emission electrons.

Because of the very high average current in the SNS Ring (18.9 A for 1×10^{14}) the wire would burn out very rapidly. By locating the filament at a point where only 1% of the beam intercepted the wire, the expected temperature rise could be kept to approximately 600^{o} K for a 20 micron carbon wire located at a beta-average. Because of the small mass in the beam the resulting radiation would not be a problem but scattering off the wire will increase the divergence of the beam. This has been calculated to be approximately 0.1 mrad, which must be added in quadrature to the divergence at the wire location. At a beta-average location this would be 8.3 mrad so the emittance growth should be small.

Another question is whether the longitudinal distribution at the transverse periphery of the beam represents the central distribution of the beam. This will need further study, however, it certainly will give a measure of some beam being in the gap and show the effects of various tuning strategies on reducing it .

Secondary Emission

In the case of secondary electron collection the applied electric field must be significantly stronger than the beam space charge field. Because the bunch is so long the longitudinal fields within the bunch are small. If we consider a secondary electron just outside the bunch it will see the field due to the beam long only along one quadrant of the ring. In the worst case this amounts to only about 40% of the beam. Assuming the beam to be an ellipsoid with a full length equal to about 50 meters and a radius of 2 cm the field 2 cm outside the bunch is 718 V/meter for an intensity of 2 x 10^{14} protons. An electrode with 1 kV sitting at the edge of the beam pipe would over power the beam space charge and accelerate the secondary electrons to a collector. Assuming a 2 % secondary emission coefficient for the wire surface approximately 10^7 electrons will be liberated if 10^{-4} of the full beam is in the gap. This is approximately 6.4 μA averaged over the 250 nsec gap duration. Using a gated micro-channel plate (MCP) in front of the collector can provide a gain of 10^3 to 10^4 for a single layer MCP and 10^6 or more for a dual layer MCP. This is more than sufficient for the turns later in the cycle but for the first turn there will only be 10^4 electrons over the whole gap and statistics may be poor.

Secondary Radiation

It is also possible to observe the radiation from the interaction of the beam on the wire using a gated photomultiplier with a scintillator. One such device is the R5916U manufactured by Hamamatsu[6] . This unit uses an MCP with a gain of 10^5 which can be gated on and off in under 1 nsec. An estimate of the signal using a standard AGS semi-circular paddle scintillator with 10 cm inner radius and 20 cm outer radius and 1 meter arm, gives 1.4 x 10^3 events for a 10^{-4} gap beam. While this is considerably smaller than for the secondary emission collection it eliminates the complication of the HV accelerating electrode. Note that this represents only 1 event for the entire first turn. Data would have to be taken over many cycles to obtain sufficient statistics. At 60 Hz repetition rate, 1000 cycles is only 16 seconds.

Residual Gas Ionization as BIG Monitor

As the beam passes through the vacuum chamber it ionizes the background gas. The ionization is directly proportional to the local beam density and the number of molecules of residual gas in the beam path. This is the basis of the Ionization Profile

Monitor (IPM) which is often used to measure the beam's transverse density distribution in a non-intercepting way. The ionization electrons are swept across the beam pipe by the applied electric field and detected on segmented collectors to provide the profile information. Clearly the beam in the gap could be measured in this way although just a single collector would be required since only the total intensity is desired. Since the transit time for electrons is short (6.75 nsec for 5 kV bias over 20 cm gap), this approach has the potential of being a non-intercepting measurement with good time resolution. The SNS vacuum must be good to minimize beam loss but that means that there will be few beam-gas interactions. Raising the background vacuum pressure locally from 10^{-9} to 10^{-7} Torr will bring the number of ionizations in the gap to 443 assuming 10^{-4} of the bunch intensity. This pressure bump will already be provided for the IPM, so inclusion of a BIG monitor in that vacuum chamber will not further perturb the ring vacuum. However, this is a very small number of events. Note that using an MCP, gated to reject the main bunch beam, will not change the number of events, although it will make the signal amplitude detectable. Using this approach accumulation over perhaps 10^4 cycles will be needed to make a measurement for the first turn.

Summary

A number of techniques for observing the Beam-In-Gap have been considered. Each has advantages and disadvantages but there is no obvious best method. The kicker approaches offer the advantage of eliminating the beam in the gap in a controlled way, but would be expensive. The residual gas monitor is non-intercepting but must accumulate data over many Ring cycles to obtain suitable statistics for a first turn measurement. The data rate could be increased by inserting a wire intercepting 1% of the beam, but this may not represent the distribution in the core beam, causes loss and is subject to mechanical failure. Using a beam current transformer was initially considered the most desirable since it is non-intercepting but it is unlikely that a transformer with the rise time, droop time constant and overshoot could be built. It is possible that a composite of two transformers could cover the bandwidth and feedback could cancel the overshoot, making this approach practical.

The kicker approaches, both magnetic and RF, will be studied in more detail and a cost estimate developed. At the same time further work on the residual gas monitor will continue. The possibility of a small R and D contract to recognized beam current transformer vendors to develop a suitable detector will also be considered. A transformer-type monitor should be built, even if rise time and sensitivity specifications must be weakened, just as a backup to an alternative approach.

1 Plum, M., “Beam Measurements at High Intensity Storage Rings”, AIP Conf. Proc. 319, Beam Instrumentation Workshop, p72-88, Santa Fe, NM, 1993

2 Plum, M., Private communications, March 1998

3 Bergoz, J., Private communication, May 1998

4 Witkover, R. L. “A Non-Destructive Bunch Length Monitor for Proton Linacs”, Nucl. Instr. and Meth., V. 137, No. 2, 203-211, 1976

5 Feschenko, A. V., and Ostroumov, P. N., “Bunch Shape Measuring Technique and its Application for an Ion Linac Tuning”, Proc. 1986 Linear Accel. Conf., SLAC report 303, Sept 1986, p 323

6 Hamamatsu Corporation, 360 Foothill Rd, PO Box 6910, Bridgewater, NJ 08807

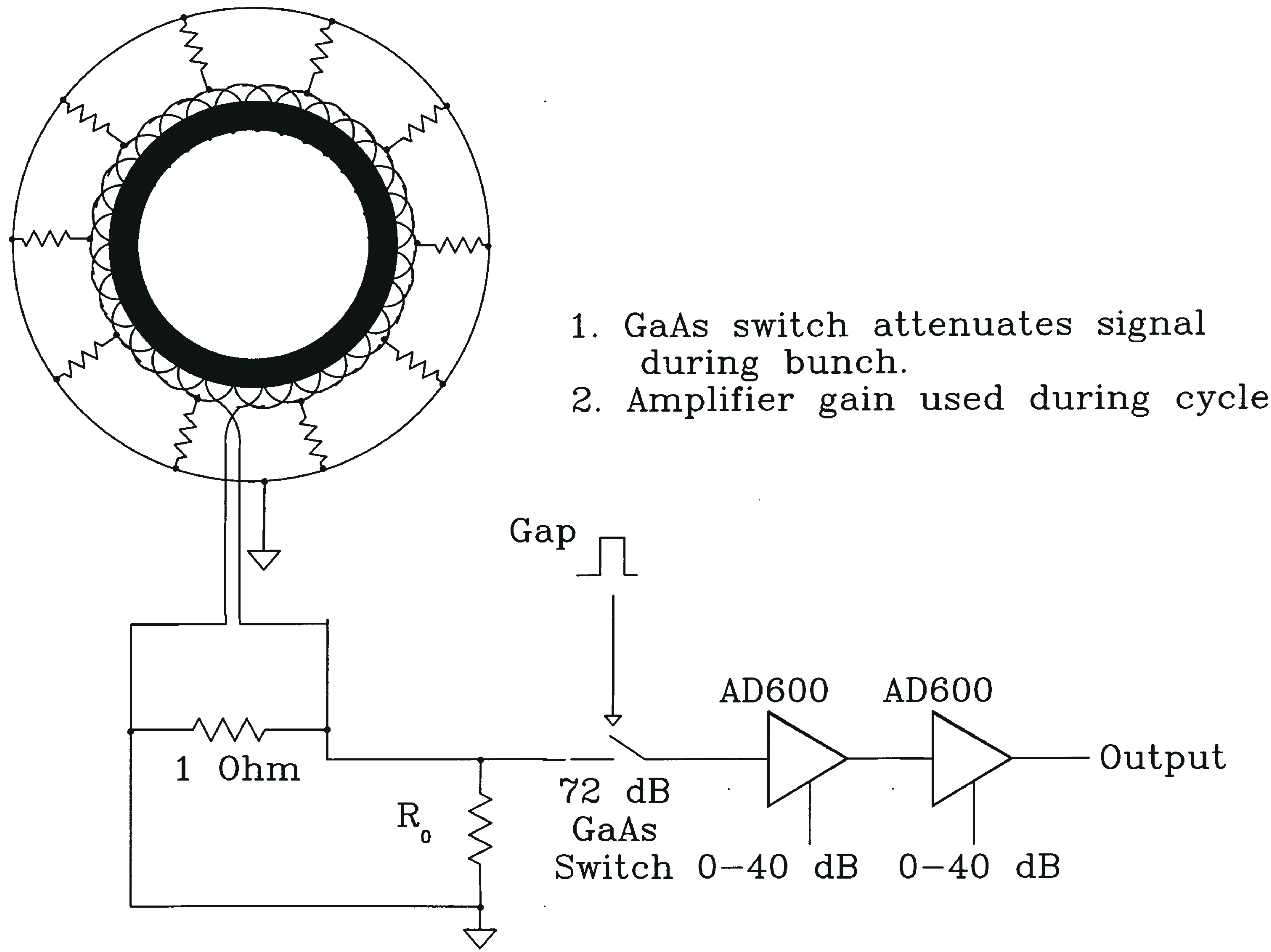

Figure 1. SNS Ring Beam in Gap Transformer and Electronics