LANSCE WIRE SCANNER AFE: ANALYSIS, DESIGN, AND FABRICATION*

M. Gruchalla#, EG&G Albuquerque Operations, Albuquerque, NM 87107, U.S.A.

P. Chacon, J. D. Gilpatrick, D. Martinez, J. Power, B. Smith,

Los Alamos National Laboratory, Los Alamos, NM 87545, U.S.A.

Abstract

The goal of the design LANSCE-R Wire-Scanner Analog Front-end Electronics is to develop a high-performance, dual-axis wire-scanner analog front-end system implemented in a single cRIO module. This new design accommodates macropulse widths as wide as 700µs at a maximum pulse rate of 120Hz. A lossey integrator is utilized as the integration element to eliminate the requirement for providing gating signals to each wire scanner. The long macropulse and the high repetition rate present conflicting requirements for the design of the integrator. The long macropulse requires a long integration time constant to assure minimum integrator droop for accurate charge integration, and the high repetition rate requires a short time constant to assure adequate integrator reset between macropulses. Also, grounding is a serious concern due to the small signal levels. This paper reviews the basic Wire Scanner AFE system design implemented in the cRIO-module form factor to capture the charge information from the wire sensors and the grounding topology to assure minimum noise contamination of the wire signals.

INTRODUCTION

One element of the LANSCE-R task is to replace a number of the aging wire-scanner systems. Both the mechanical components and the electronics are to be replaced.

The National Instruments cRIO system has been selected as the basic platform for the wire-scanner electronics [1]. To the extent feasible, commercial of-the-shelf (COTS) cRIO modules are being utilized with custom modules for specific tasks designed specifically for the LANSCE-R application. The Wire-Scanner Analog Front-end Electronics (WS AFE) is a custom cRIO module.

The WS AFE independently collects and integrates the charge from two orthogonal sensing wires and delivers the processed analog signal to cRIO digitizers. The goal for the LANSCE-R application is to provide the ability to capture macropulses as long as 700µs at a maximum macropulse rate of 120Hz. The long macropulse and the short inter-pulse period present a unique challenge in the design of the integration function of the WS AFE.

The small signal levels expected at the extremes of the beam distribution require careful attention to minimizing noise encroachment into the WS AFE signal paths. It is reasonably expected that there will be a substantial potential difference between the beam-line equipment ground and the electronics equipment ground. This represents a nuisance potential that could corrupt the wire-scanner data. Therefore, management of the grounding between the beam line and the instrumentation is critical.

DESIGN STRATEGIES

The LANSCE accelerator is a production system, as compared to a purely experimental accelerator, and the wire scanners are diagnostic tools used to manage system operation. In comparison to typical experimental venues, the magnitude and spectrum of the wire-scanner signals expected in the LANSCE accelerator are very-well bounded. This relieves some of the complexity of the WS AFE by allowing functions typically required in the wire scanner to be moved into other elements of the system. Several of the more critical design challenges are reviewed below.

Measurement Dynamic Range

The maximum total collected charge in a macropulse is a function of the wire-scanner location in the LANSCE accelerator. The dynamic range of collected charge across all locations at the distribution center is less than nominally 100. The dynamic range required in the measurement at any specific position has been set at nominally 100. Therefore, a total dynamic range of 10,000 is required in the WS AFE system so that any WS AFE unit may be utilized at any position [2].

Normally, the WS AFE would include analog gain switching to accommodate a very wide operational dynamic range. Since only a nominal 10,000 dynamic range is required in the LANSCE-R application, this may be totally provided in the cRIO digitizers. A National Instruments NI 9205 cRIO digitizer is utilized to digitize the WS AFE analog signals. The NI 9205 is a 16-bit plus sign digitizer and provides four full-scale sensitivities: ±10V, ±5V, ±1V and ±200mV. This unit provides a theoretical dynamic range of 3e6 with a basic precision of 3µV.

Measurement Sensitivity

The measurement sensitivity required is a function of how far down in the distribution data is desired at the position in the accelerator providing the lowest signals.

*Work supported by US Department of Energy
#gruch@lanl.gov

Based on historical wire-scanner data at LANSCE, a noise-limited sensitivity of nominally 100pC is adequate. The design goal is a noise-limited sensitivity of less than 1pC in the WS AFE alone [3], and better than 10pC overall.

Charge Integration

In a typical wire-scanner application, the charge collected from the wire-scanner sense wire is integrated directly in the analog electronics. A simple lossey integrator is contraindicated in the LANSCE-R application due to the long macropulse length of 700μs and the high PRF of 120Hz (8.33ms pulse period). The integrator time constant required for acceptable integrator droop and the integrator time constant required for adequate integrator reset between macropulses are conflicting.

An integrator reset signal specific for each wire scanner would normally be required to provide both high-quality macropulse charge integration and adequate inter-pulse integrator reset. However, providing separate unique timing signals for each wire scanner would substantially increase the command and control complexity of the overall accelerator wire-scanner system.

A hybrid approach for charge integration is used in the LANSCE-R WS AFE. The AFE provides a lossey analog integrator having a comparatively short integration time constant to provide adequate integrator reset between macropulses, and numeric integration is provided in the cRIO FPGA to provide integration of the total charge collected during each macropulse.

Grounding

Grounding is always a challenge in low-noise instrumentation systems. And, due to the numerous high-level devices, such as RF sources, magnets, kickers, etc., high-quality low-level instrumentation grounding in accelerator facilities is a unique challenge. In general, it must be expected that there will be substantial nuisance potentials between the beam line and the electronics.

The nature of the sensor in a wire scanner also presents a unique grounding challenge. The sense wire presents as virtually a true current source. Therefore, it has no ground reference. A simple coaxial cable from the beam line to the electronics will not provide a high-performance ground where there are significant nuisance potentials between the ends of the coaxial path.

A combination of conventional grounding and shielding is utilized with a guard system to provide a high-quality shielding of the sense-wire signal.

Sense-Wire Bias

A DC bias potential is required to optimise the charge signal. The bias magnitude and polarity are a function of the beam energy, particle species, wire material, etc. A bias range of zero to ±50V has been specified for the LANSCE-R wire scanners. The wire bias is provided through the WS AFE from an external power supply.

Wire Integrity Validation

An important element of a wire-scanner system is a means to validate the integrity of each sense wire. It is also useful to have means to validate the integrity of the wire-validation system to assure that a failure in the integrity system does not falsely indicate a broken wire and subsequent unnecessary removal of a wire scanner from the beam line.

The integrity of the sense wire is provided by simply driving a test signal through the wire and sensing the resulting signal with the data-acquisition electronics.

CIRCUIT DESCRIPTION

A simplified schematic diagram of one WS AFE signal channel is shown in Figure 1. Two independent signal channels are implemented in a single cRIO module to allow instrumentation of both wires of a typical two-wire wire-scanner system in a single cRIO module.

Sense-Wire Interface

Access to both ends of the sense wire is necessary to allow the wire integrity to be validated. Referring to Figure 1, both ends of the sense wire are instrumented separately and the signals summed. It is important to note that this configuration is not a differential measurement since the wire is not a differential source.

The signals from each end of the sense wire are communicated to the vacuum interface on coaxial cables. Since this path is very short, and is inside the beam pipe, grounding is much less critical than the long cable path to the instrumentation. Therefore, this short length of coax is simply grounded to the beam-line equipment ground inside the beam pipe. This allows the use of standard radiation-tolerant coax and standard vacuum feed-through connectors.

From the vacuum interface to the instrumentation, the two wire signals are carried on separate triaxial coax. The use of a triaxial cable configuration allows the signal path to be both shielded and guarded.

Some RF signal is expected to be collected by the sense wires. The frequencies of these RF components are well beyond the bandwidth needed in the WS AFE. This RF energy could corrupt the operation of the WS AFE input circuitry if allowed to enter the sensitive inputs of the amplifiers. Therefore, RF energy with spectral components outside the operational bandwidth of the analog circuitry is filtered out by the R1-C1 pole at 100kHz.

There is also a concern that the AFE input circuitry could be damaged by electrostatic discharge (ESD) events. For example, if the instrumentation cable were disconnected during beam operations, charge collected by the sense wire could charge the cable capacitance to high enough potentials to damage the AFE input circuitry when reconnected. To protect the AFE input, a transient-protection network is provided immediately at the input to the first amplifier as shown in Figure 1. Resistor R2 provides a current-limiting impedance to protect the transient-protection network and to improve the effectiveness of the protection provided.

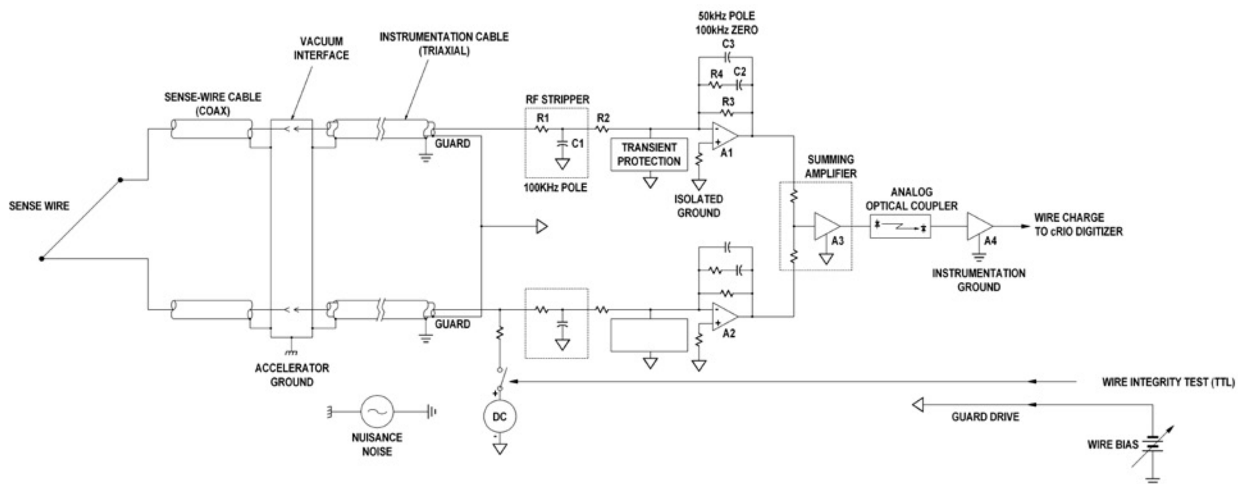

Figure 1: Single Channel of the LANSCE-R Wire Scanner-Analog Front-end Electronics

A second network pole is introduced by the time constant of R2 and the capacitance of the protection network. The value of R2 is selected to place that pole at nominally 500kHz to limit the input noise bandwidth.

Input-Amplifier Configuration

The wire signal current is delivered to the input to amplifier A1 configured as a transimpedance amplifier. The DC gain of this configuration is equal to R3. Capacitor C2 introduces a dominant network pole at 50kHz. This is the basic response bandwidth of the AFE. Resistor R4 and Capacitor C2 introduce a network zero at 100kHz to cancel the pole of the RF stripper. This provides a true integral response above 50kHz. Capacitor C3 provides a final high-frequency pole to define the overall noise bandwidth of the first AFE stage.

Two identical signal paths are utilized to sense both ends of the sense wire. As noted above, this is not differential sensing. When charge is collected, the charge is divided between the two signal paths and each charge component is processed in the corresponding input stage.

The two wire signals are simply summed in the summing amplifier A3. The output signal of A3 represents the total charge collected by the wire sensor.

Dielectric Isolation

Dielectric isolation of the input circuitry is provided by a high-performance analog optical coupler. The coupler utilized (HCNR200) provides 5kV RMS isolation (recognized under UL-1577). The -3dB bandwidth of the isolator was measured to be in excess of nominally 3MHz, The specified transfer error and nonlinearity is 0.01%. All these parameters are well within the requirements of the WS AFE.

Output Stage

The optical isolation is followed by a buffer amplifier referenced to the cRIO instrumentation ground. For LANSCE-R, since the overall dynamic range required is well within the signal-to-noise ratio of the AFE at full-scale output, and well within the capabilities of the digitizers, the gain of the WS AFE is fixed to provide a ±5V full-scale output for the largest wire signal expected within the LANSCE accelerator.

Bias

Typically, a bias electric field must be provided to minimize recapture of secondary electrons radiated from the wire. For the LANSCE-R system, the most straightforward approach to providing this bias is to bias the sense wire itself. This is accomplished in the LANSCE-R WS AFE by elevating the entire input circuitry to the desired bias potential. Since the input amplifiers are of a transimpedance configuration, the input node of the amplifier is forced to the reference ground of the input stages. By elevating this input-circuit reference-ground net to the desired bias potential, that bias potential is delivered directly to the sense wire. This is shown in Figure 1. The bias potential is delivered externally to the WS AFE cRIO module and is applied directly to the reference ground of the input stage.

Frequency Response and Charge Integration

The overall response of the basic WS AFE is flat from DC to 50kHz, and then breaks with a true first-order pole to nominally 1MHz. Above 1MHz, a second pole is introduced to limit the system noise bandwidth. Therefore, above the 50kHz pole, the WS AFE is self integrating to 1MHz. A complete integral response of the wire signal is achieved by providing numeric integration with a numeric zero at 50kHz to cancel the hardware pole at 50kHz. Since the DC component is not typically of interest in a wire-scanner system, the DC component is numerically removed prior to integration.

Data are collected over the entire macropulse, and numeric integration of the wire signal above 50kHz is provided real time in the cRIO native VIRTEX 5 FPGA and cRIO Power PC. This allows both the temporal characteristics of each macropulse (with 50kHz bandwidth) as well as the overall macropulse integrated charge to be recorded and displayed on a pulse-by-pulse basis.

Wire-Integrity Verification

Sense-wire integrity is provided by passing a test current through the wire and recording the response through the normal data-acquisition path.

In Figure 1, a DC potential of nominally 100mV is switched into the input path of the WS AFE by means of an external TTL signal. When this potential is applied, the two input amplifiers operate as voltage amplifiers having a nominal gain of R3/R2 with a 50kHz bandwidth.

The test signal is delivered directly to Amplifier A2, and in turn to the summing amplifier A3. If the sense wire is intact, this test signal is also delivered to amplifier A1 through the sense wire, and to the summing amplifier.

The output signal level with an intact wire is the sum of the two signals of amplifiers A1 and A2 respectively. However, if the sense wire is broken, no signal is delivered to amplifier A1. The resulting sum is then nominally one half that seen with an intact wire.

This method of wire-integrity validation not only provides verification of the sense-wire continuity, but also provides verification that the wire-integrity circuitry is operational. This assures that a failure in the wire-integrity system will not be interpreted as a wire failure.

Grounding and Shielding

High-quality grounding is critical due to the small signal levels expected at the extremes of the beam distribution and particularly at the accelerator locations having the lowest peak signal levels. This is further complicated by the fact that the sense wire presents as virtually a true current source with no reference to a signal ground. But, the AFE input stage must measure the input signals with respect to its own ground reference.

The instrumentation alcoves are approximately 50m from the beam line. It is reasonably expected that there will be a potential comprised of various signals between the beam-line equipment ground and the instrumentation equipment ground. This potential is shown as the "Nuisance Noise" source in Figure 1. One of the known nuisance noise sources is the motor-drive signal to the wire-scanner actuator mechanism.

When a coax is utilized to carry the sense-wire signal, and its shield is connected to the beam-pipe and the instrumentation equipment grounds respectively, the nuisance potential between the beam pipe and the instrumentation grounds presents this nuisance potential across the shield which introduces a nuisance current in the shield of the coax.

The shielding-effectiveness transfer function of the coax results in a potential on center conductor, and the capacitive coupling between the shield and center conductor results in a capacitive coupling of shield potentials to the center conductor. These effects can produce substantial noise on the center conductor.

The noise performance may be improved by guarding the input signal node along the entire signal path from the wire sensor to the AFE. A guarding system is utilized in the LANSCE-R wire-scanner system to provide a high-level of noise rejection. A triaxial coax is utilized with the outer shield connected between the beam-line and instrumentation equipment grounds in a conventional fashion. This outer shield provides protection from radiated fields. The inner shield of the triax is driven by the guard-drive signal in the WS AFE.

The guard drive is a low-impedance source that effectively forces the guard shield to the same potential as the input-signal potential. Since this inner shield is forced to the same potential as the signal conductor, the signal conductor is protected, e.g., shielded from, coupling from the outer shield to the inner shield.

The transimpedance input-stage configuration of the WS AFE shown in Figure 1 forces its input node to the amplifier reference potential, e.g., the virtual ground of the input-stage. Since the input-node potential is at the input-stage ground reference potential, the guards must be driven to that same reference potential. In Figure 1, the guard shields of the triax s are connected to the input stage isolated reference ground. This isolated ground is driven by the bias source.

The bias source is a low-impedance source which effectively holds the guard shield of the triax at the bias potential. This guarding configuration shields the center conductor of the triaxial cable from conducted and radiated noise impressed on the outer shield.

SUMMARY

The design of the new analog front-end electronics for the LANCE-R wire scanner has been provided in this work. Details of a wide-bandwidth transimpedance input stage with numeric charge integration to meet the macropulse width and PRF requirements has been described. The method of providing bias directly on the sense wires was reviewed. The grounding and guarding topology to provide low-noise charge collection was detailed.

REFRENCES

[1] National Instruments, Inc., Austin, TX 78759-3504, www.ni.com/compactrio.

[2] J. D. Gilpatrick, D. Barr, L. Day, D. Kerstiens, M. Stettler, R. Valdiviez, M. Gruchalla, J. O'Hara, J. Kamperschroer, "Beam-Profile Instrumentation for a Beam-Halo Measurement: Overall Description, Operation, and Beam Data," DIPAC'01, Grenoble, May, 2001 CT05, p. 76 (2001); http://www.JACoW.org.

[3] M. E. Gruchalla, J. O'Hara, D. Barr, T. Cote, L. Day, D. Gilpatrick, M. Stettler, D. Martinez, "Beam Profile Wire-Scanner/Halo-Scraper Sensor Analog Interface Electronics," PAC'01, Chicago, June, 2001, WPAH098-3, p. 2314 (2001); http://www.JACoW.org.