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IMPLEMENTATION OF TRANSIMPEDANCE ANALOG FRONT – END CARD FOR LOS ALAMOS NEUTRON SCIENCE CENTER ACCELERATOR WIRE SCANNERS *

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Abstract

The Los Alamos Neutron Science Center's (LANSCE) Accelerator Operations and Technology division - Instrumentation and Controls (AOT-IC) team executed a project that implemented a new Analog Front-End (AFE) card for their wire scanner's Data Acquisition (DAQ) system. The AFE accommodates the signal amplification and noise reduction needed to acquire essential measurement data required for beam diagnostics for LANSCE accelerator. Wire Scanners are electro-mechanical beam interceptive devices that provide cross-sectional beam profile measurement data fitted to a Gaussian distribution that is then extrapolated to provide beam shape and position. The beam shape and position information allow the operator to adjust parameters such as acceleration, steering, and focus to provide optimized beam delivery to targets. The project included software and hardware implementation that eliminated the dependency on legacy systems and consolidated various AFE designs for diagnostics systems into a single design with 11 gain settings ranging from 100 nA to 40 mA at 10 V full scale to accommodate its future applications on other diagnostics systems.

BACKGROUND

The LANSCE facility utilizes various beam diagnostics devices for operators to adjust beam parameters such as acceleration, steering, and focus to provide efficient and effective beams to all five experimental areas. Wire scanners are interceptive beam diagnostics devices with a mechanical actuator assembly and a single or pair of Silicon Carbide (SiC) or Tungsten (W) wires (sensor) mounted vertically and/or horizontally to the sensor fork mount as shown in Fig. 1.

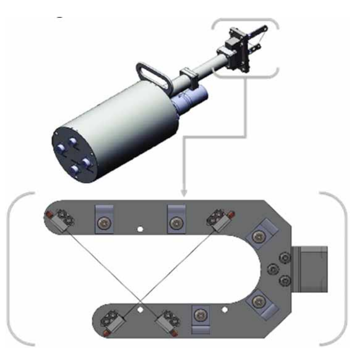

Figure 1: Wire Scanner and Sensor Fork Assembly.

When the beam impinges on the wires, current resulting from the emitted secondary emission yield is deposited on the wire; this current is proportional to the beam current [1]. Since the wire's position is scanned in the beam pipe, the wire scanner provides the transverse vertical and horizontal profile measurements with a Gaussian fit, as shown in Fig. 2.

The data from the wire scanner is obtained by hardware and software implementation of the QAC (Quad Actuator Controller) DAQ, National Instruments – CompactRIO (cRIO) Systems. The QAC DAQ cRIO system controls movement and acquires data. The user interface JAVA program analyzes and displays the result of the received scan data [2]. The AFE card is the component of the DAQ that acquires beam-impinged secondary electron current flow from the wires. The AFE is a compact Peripheral Component Interconnect (cPCI) form factor card supporting 16 channels, assuming one channel for each axis, supporting eight wire scanners per card.

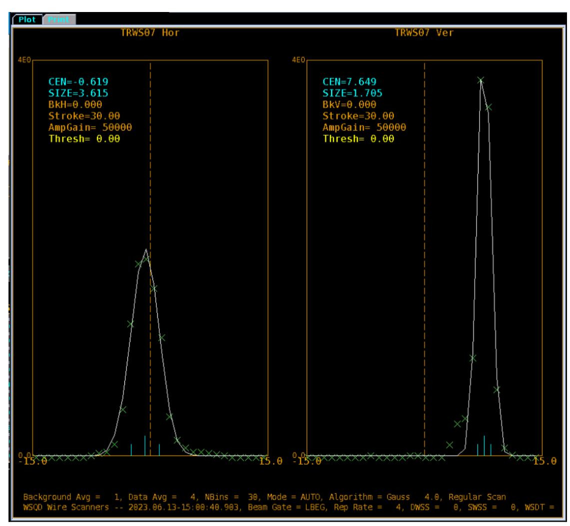

Figure 2: LBEG (Long Bunch Enabled Gate) Beam scan of TRWS07 Wire Scanners.

During the implementation of the QACDAQ system for wire scanner systems in the transition region and downstream areas, the LANSCE Harp AFE was used. The LANSCE Harp AFE full scale range is from 3 µA to 270 µA and was not sensitive enough for typical Wire scanner application [3]. As shown in Table 1, LBEG is a higher current beam with 50 times greater macro pulse average current and 100 times greater charge per pulse than MPEG (Micro Pulse Enabled Gate) [4]. Therefore, the LANSCE Harp AFE was adequate in performing wire scanner scans of the LBEG beam but not for MPEG.

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Table 1: LBEG and MPEG Comparison

Descriptions	LBEG	MPEG
Pulse Spacing	358 ns	1800 ns
Pulse Duration	290 ns	20 ns
Pulses Per Macro Pulse (625us)	~1746	~347
Average Current	100 µA	2.0 µA
Charge/Pulse	5.0 µC	.05 µC
Protons/Pulse	3.1×10^{13}	3.1×10^{11}

NEW DESIGN

Design Requirements

Table 2: Design Requirements

ID	Requirement
1	Same Form and Fit as the LANSCE Harp AFE with 16 input channels
2	LBEG and MPEG beam scans capable
3	+/-50 VDC Bias Input Capability
4	Gain selection options for user optimization which cover expected beam currents
5	Protected Input
6	Greater than +/-5 VDC Full Scale Output

Dynamic Range

The dynamic range for expected induced current had to be determined to design a new AFE. Induced sensor current measurements of strategic wire scanner locations were performed for LBEG and MPEG beam during beam development time using an off-the-shelf Thorlabs, PDA200C - Benchtop Photodiode Amplifier [5]. We determined the range of induced current for the wire scanners to be between 300 nA and 10 µA, giving us a better understanding of potential gain ranges for the new AFE design.

Bandwidth

At LANSCE, two-beam pulse widths are used: a pulse width of 625 µs (1.6 kHz) is typically used for the production beam with repetition rate of 120 Hz, and 150 µs (6.6 kHz) is generally used during beam tuning efforts with repetition rate of 4 Hz.

Design Approach

It was necessary to use an amplifier scheme that accepts current to amplify low current signal accurately and stably from the wire scanner wires to a usable voltage level. Transimpedance amplifier (TIA) circuit design is typically used to convert and amplify low current output of sensors such as Photodiodes to a proportional output voltage. With the successful use of the Thorlabs, PDA200C - Benchtop Photodiode Amplifier during testing under nominal beam delivery conditions, we gained assurance of the effectiveness of the TIA design approach.

The TIA circuit in Fig. 3 presents near 0 voltage and impedance to the current source, maximizing signal transfer from a high-impedance current signal source. Due to this characteristic and with a known voltage output requirement of +/- 10 V and the desired current range for each gain stage shown in Table 3, the values of feedback resistors, Rf, can be calculated using Eq. (1).

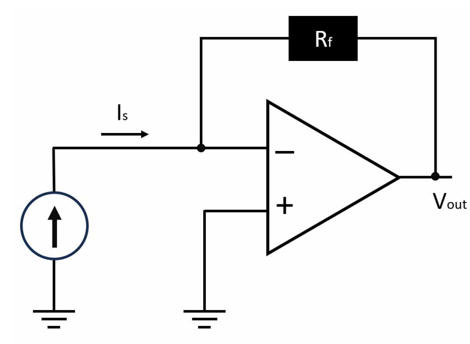

Figure 3: TIA Circuit

Table 3: New AFE Gain Stages

Gain#	I_{Min}	I_{Max}	V_{Min}	V_{Max}	f_p
0	0	100 nA	-10 V	+10 V	1.6 kHz
1	0	500 nA	-10 V	+10 V	1.6 kHz
2	0	2.5 µA	-10 V	+10 V	1.6 kHz
3	0	12.5 µA	-10 V	+10 V	1.6 kHz
4	0	10 µA	-10 V	+10 V	6.6 kHz
5	0	50 µA	-10 V	+10 V	6.6 kHz
6	0	250 µA	-10 V	+10 V	6.6 kHz
7	0	1.25 mA	-10 V	+10 V	6.6 kHz
8	0	5 mA	-10 V	+10 V	6.6 kHz
9	0	20 mA	-10 V	+10 V	6.6 kHz
10	0	40 mA	-10 V	+10 V	6.6 kHz

$$V_{Out} = -I_{in}R_f \text{ or } R_f = \left|\frac{V_{out}}{-I_{in}}\right| \quad (1)$$

At higher input frequencies, f_p, it is important to ensure the feedback network doesn't interact with the open loop gain of the op-amp to cause instability. Without compensation, a frequency causes a gain of 0 dB and complete phase reversal to the input, causing positive feedback. Even a tiny input capacitance results in stability issues. Parasitic capacitance in the circuit is unavoidable; therefore, adding a feedback capacitor, C_f, in parallel with a feedback resistor, R_f, as shown in Fig. 4, is crucial for compensating these undesired effects [6].

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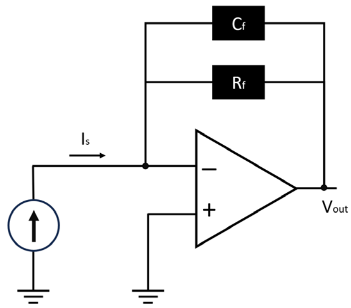

Figure 4: TIA Circuit Layout with Feedback Capacitor.

Figure 5 shows the transient response of how an uncompensated TIA circuit is marginally stable with substantial ringing, causing the output to overshoot. On the other hand, Fig. 6 represents a compensated TIA transient response, which is stable with a clean step response.

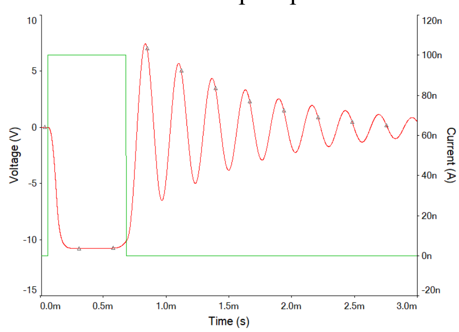

Figure 5: Transient Response of Uncompensated TIA.

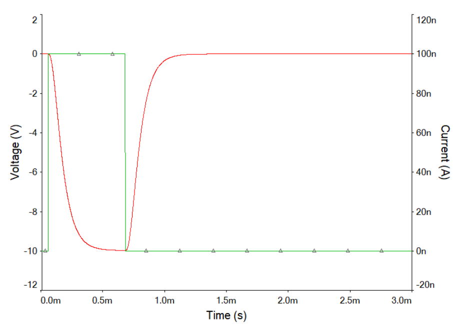

Figure 6: Transient Response of Compensated TIA.

Equation 2 can be used to calculate C_f, using the computed value for R_f and f_p given in Table 3 for each gain stage. Lastly, to ensure that the Gain Bandwidth Product (GBWP) of the op-amp is sufficient for each gain stage configuration, Eq. (3) can be used. C_{in} in Eq. (3) is the total input capacitance, which includes the capacitance for the input cable and sensor along with amplifier common mode and differential mode capacitance. The calculated GBWP (right-side) must be less than the GBWP of the op-amp; otherwise, it will lead to instability and a non-linear response of the TIA output [7].

$$C_f \leq \frac{1}{2\pi f_p R_f} \quad (2)$$

$$GBWP > \frac{C_{in}}{2\pi * R_f * C_f 2} \quad (3)$$

Design Challenges

The design's main challenge was finding an operational amplifier (op-amp) with low bias current and high GBWP to meet the gain and bandwidth requirements of all the gain stages listed in Table 3. We narrowed our selection to the Texas Instruments, THS4631- High-Speed FET-Input Operational Amplifier based on performance, cost, and availability. It was the only op-amp available with GBWP over 200 MHz that supported +/-12 VDC dual input supply rail that was available at the time of the development.

Final Design Discussion

Figure 5 shows the simulation result for Gain 0, which required the highest gain of 100 M, and the transient response is stable and has a clean step response when excited with 100 nA. Figure 7 shows the final fabricated assembly and Fig. 8 shows the final single-channel layout of the TIA circuit of the new AFE design. The design includes 11 selectable gains divided between seven high and four low bandwidths, shown in Table 3.

Figure 7: New TIA AFE Assembly.

The gain stages 0 to 3 for low bandwidth and gain stages 5 to 10 for high bandwidth are designed to have 20% overlap higher to lower gain stage to ensure continuity between gain stages. This overlap helps in the case of a user experiencing saturated voltage output at selected scan gain selection, then lowering the gain still provides overlap to better capture the signal within an acceptable range.

During beam development, we had issues with unknown transient voltage damaging the TIA inside the Thorlabs, PDA200C - Benchtop Photodiode Amplifier. Hence, to make the design robust, we added a dual diode, D1, as shown in Fig. 8, to protect the amplifier from overvoltage. The current limiting resistor, R26, is also placed at the non-inverting input of the amplifier, as shown in Fig. 8.

A low pass filter with a 6.6 kHz corner is added to improve noise attenuation. Gain stages 8, 9, and 10 were added later to accommodate other beam diagnostics systems using the same QAC DAQ system.

Even though the dynamic range for the sensor current was between 300 nA and 10 µA, we added gain 0 covering the 0-100 nA current range to have the capability to measure lower current for additional diagnostics purposes.

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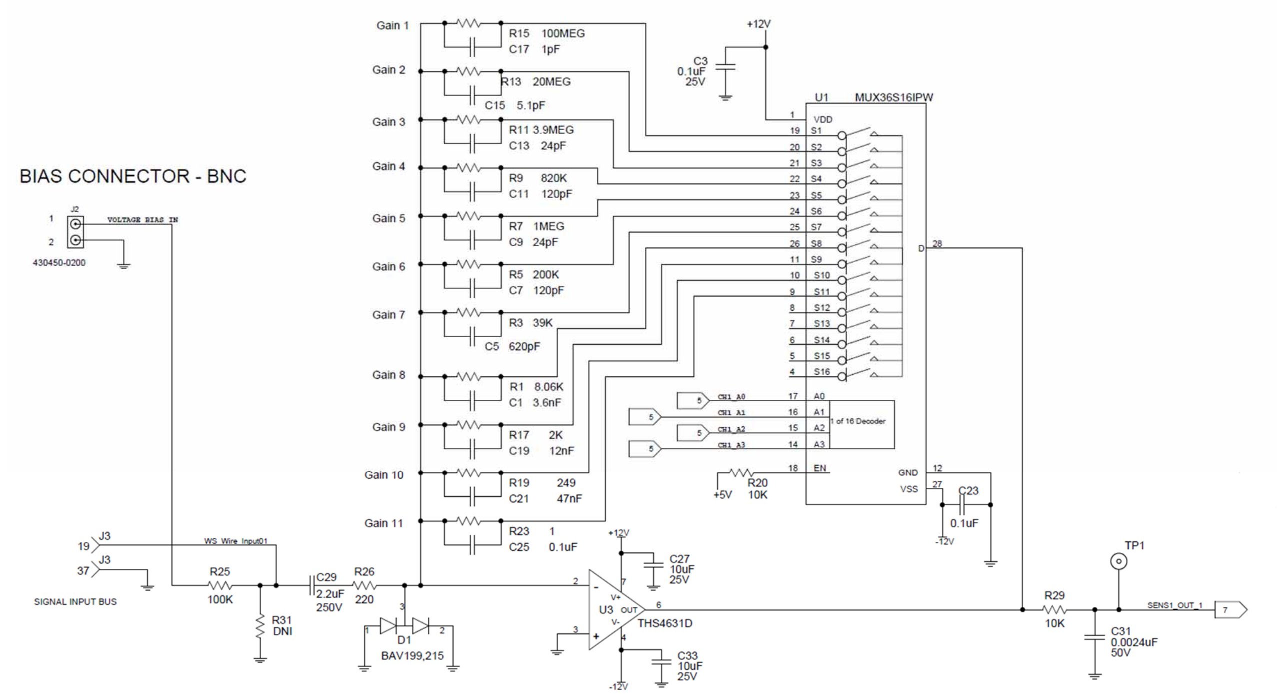

Figure 8: Single Channel Layout of New Transimpedance AFE.

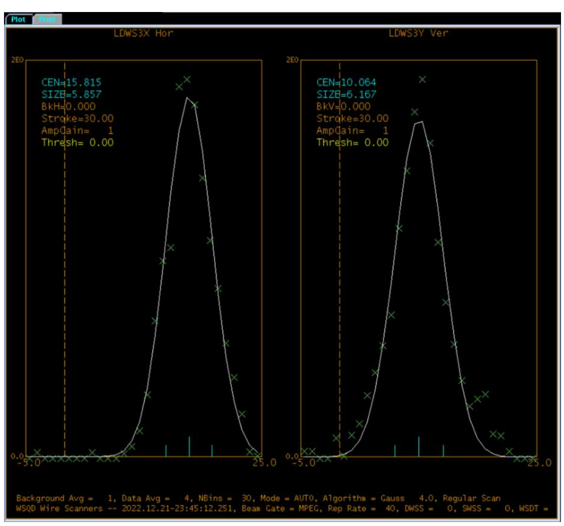

Figure 9: MPEG Beam scan of LDWS3X and LDWS3Y Wire Scanners.

CONCLUSION

During the V&V (Verification and Validation) of the new AFE, hardware and software implementation it showed that the new Transimpedance AFE design for the DAQ system meets all the design requirements listed in Table 1. Figure 2 and Fig. 9 show successful wire scanner scans with LBEG and MPEG beam taken during beam development time, respectively. Both scans show a good Gaussian fit with a clear beam center and size for horizontal and vertical axes providing essential data for beam tuning. The new design has adequately addressed design and functional limitations of the LANSCE Harp AFE providing a dynamic gain range to measure the induced sensor current with accuracy and stability.

Also, with additional gain stages out to 40 mA full scale, future efforts can be made to convert all diagnostics systems to the new Transimpedance AFE, streamlining and reducing the life-cycle management cost of maintaining configuration. Additional opportunities exist to use the same design scheme for other DAQ systems but in a different form and fit.

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