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DEVELOPMENT OF A LOW INTENSITY CURRENT MONITOR SYSTEM*

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Abstract

This report documents the development of a current transformer system used to measure pulsed ion beam currents with a wide dynamic intensity range (nA to mA, a factor of 10^6). Peak beam currents at the LAMPF accelerator typically range from 100 nA to 40 mA with pulse widths varying from 30 to 1000 μ s. Signal conditioning of the peak current output provides an average current readout with a range of 1 nA to 2 mA, noise of approximately ± 0.5 nA, and accuracy of $\pm 0.1\%$. Since the system has proved stable and highly reliable, calibration is performed yearly. The prototype unit was built in 1985 and the final production unit was completed in early 1989.

Introduction

The Los Alamos Meson Physics Facility (LAMPF) presently operates three pulsed beam injectors, generating H^+ , H^- , and polarized H^- (P^-) ion beams over the energy ranges of 113 to 800 MeV. Each injector is capable of variable pulse widths (typically 800 μ s) and repetition rates (maximum frequency of 120 Hz). Typical peak currents range from 30 μ A for the P^- injector to 40 mA for the H^+ injector. Beam duty factors are limited to approximately 10%, but can be varied according to the needs of the experimental programs.

Accelerator operation requires a real time device that (1) can measure low intensity beams, (2) is nonintercepting, (3) has high gain stability, (4) is independent of the beam energy, and (5) has an absolute accuracy near 0.1% of full scale.

Nonintercepting current monitors are used to tune and operate the accelerator as well as to measure the beam currents delivered to

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the various experiments. The current monitors also provide protection against excessive loss by measuring transmission through various sections of the facility. This information is then supplied to the Hardware Transmission Monitor¹ (HWTM), which converts peak to average current and shuts off beam if a preset trip level is exceeded.

The High Sensitivity Current Monitor System (HSCM) is the latest in a sequence of evolving systems based on toroidal current transformers. The original installations were designed only for high-intensity beams.

The installation of the Lamb-Shift Polarized Source in 1977 provided the incentive to develop an accurate, reliable, nonintercepting current monitor that could measure both high and low intensity beams. When performing well, this source would generate 1 μA peak polarized current in the low energy transport with approximately 70% transmission to the experimental areas. In 1989 it was replaced by an Optically Pumped Polarized Ion Source (OPPIS). Peak polarized beam current in the transport is typically 15 to 30 μA . Approximately 20% reaches the experimental areas with the loss due to bunching efficiency, beam chopping and accelerator acceptance.

To use this device as a real time tuning aid, a system that accurately transmits analog signals over the length of the accelerator (0.5 mile) to the operator control room is required.

The desired response specified a current measuring system with a dynamic range of $10^6:1$ and an input of 40 mA peak current providing a full scale output of 10 V. This meant that 40 nA of current provide 10 μV output from the initial stage. The major problem was minimizing the noise in the input stage.

Physical Description

There are three models of low intensity current monitors in service that are basically scaled versions of the first production design (4.0 inch bore). They fit three LAMPF standard beam pipe diameters. All further references to dimensions will pertain to the initial production unit.

The toroid is a 2-mil Superalloy tape-wound core (O.D. = 10 inches, I.D. = 5 inches, length = 4 inches) vacuum potted in epoxy. Two hundred turns of 20-gauge copper magnet wire are wound over the

core. The core is epoxy vacuum potted to provide stabilization of the windings and dimensional definition of the toroid. The potting process causes a 40 to 50% loss of permeability. This was considered when determining the correct toroid size to achieve the minimum inductance requirements.

The toroid is encased in a Mu-metal canister to provide an electromagnetic (EM) shield. To optimize shield effectiveness the length of the inner canister was determined to be twice the diameter of the beam-line opening in the Mu-metal plus the toroid height. This 14 inch cylinder is installed in another Mu-metal cylinder 18 inches long. The final shield is a steel cylinder 14 in. long and 18.5 in. in diameter, with 0.25 in. thick walls. This cylinder, which has removable end plates, serves as the outer chassis. Four insulated spring supports provide the ground isolation and mechanical decoupling from beam line support structure and the beam line. The outer chassis is suspended by the springs within a rectangular steel box structure, lined with sound-absorptive material, that functions as an anechoic chamber. See Figure 1 below.

Figure 1 Cross Section of the High Sensitivity Current Monitor

A sheet of insulating material internally attached to the outer chassis provides the support structure for the amplifier card, zeroing card, and the gating circuit. There are penetrations in the cover plates for the power and signal connections. An external NIM-bin chassis houses the final stages of zeroing and signal conditioning. See figures 2 through 4.

Presently there are five current monitor units on line. A spare unit is used for electronic maintenance and development.

Design

Noise Minimization

Minimizing the noise while maximizing the signal-to-noise ratio (SNR) was the prime consideration in the development of this system. This is accomplished by:

1. selecting a toroid core material with a permeability such that a large inductance can be developed with a minimum core size and a minimum number of coil turns.

The inductance was large enough that the L/R time constant is not a factor in the design. If L/R is small in comparison to the beam pulse width, the signal will droop.

2. limiting the bandwidth of the device to approximately 10 kHz.

This frequency range is a good compromise between attenuating the high-frequency noise components and obtaining an analog output that is a true representation of the input.

3. using electronic filtering techniques and gating of the offset voltage to reduce the low-frequency noise.

4. selecting electronic components that have low voltage and current noise densities.

Earlier attempts at designing a low intensity current monitor were unsuccessful. With the development of low noise density electronic components, the project was renewed and successfully completed.

5. laying out signal, power, and chassis grounds to eliminate ground loops and to prevent power supply return currents from flowing through signal return paths.

Figure 2 HSCM 2.0 inch Bore, Acoustic Shell

Figure 3 HSCM 2.0 inch Bore, Outer Chassis

Figure 4 HSCM 6.75 inch Bore, Electronics

Signal and gating cabling is shielded and physically separated to minimize cross coupling of gating noise.

Analog and digital circuitry are placed on separate printed circuit boards with individual power supplies to minimize gating feedthrough. The power supplies are well regulated and located remote to the current monitor to minimize the 60 cycle induced pickup.

6. shielding the toroid from electromagnetic fields with concentric Mu-metal cans and a steel outer chassis.

The prototype design had a single Mu-metal shell, but this was insufficient to shield the toroid from accelerating RF cavity leakage fields (201.25 MHz). The permeability of the shielded material is graded to minimize the effects of magnetic saturation and thus increase its effectiveness to shield external fields. The outer shield is C1010 steel, the center shield is AD-MU-00 and the inner shield is AD-MU-80. The number and size of the penetrations in the shielding were minimized.

7. suppressing microphonic noise.

This is accomplished by decoupling the chassis from the beam line support structure and placing a box lined with sound absorptive material around it.

The toroid windings are also potted to minimize generating noise currents due to interaction with external magnetic fields.

Electronic Design

The HSCM system was designed using a noise voltage and current model. It consists of an ideal (noiseless) device connected to voltage and current noise sources. In the analysis the correlation coefficient between the voltage and current noise sources was assumed to be zero. Figure 5 shows the noise voltage and current model that was used to determine the components in the transimpedance (I to V) amplifier. The primary design objective was to achieve an SNR equal to 1 with peak beam current, I_{BEAM}, equal to 20 nA.

The inductance of the toroid (L) and the current into the initial stage of amplification (I_i) is given by

$$L = k_L \times N^2 \quad \text{and}$$

$$I_i = I_{BEAM}/N$$

where N equals the number of turns and k_L the inductance to turns-squared ratio.

$$R_f C_f = 15.9 \mu s$$

$$L = k_L N^2$$

$$I_i = I_{BEAM} / N$$

Figure 5 Noise Voltage and Current Model

If we assume all noise sources are random and uncorrelated, then the noise power in the system is additive^{2,4}.

Total RMS noise of the circuit (V_{nt}) is given by

$$V_{nt} = \sqrt{V_{ne}^2 + V_{ni}^2 + V_{nr}^2}, \quad (1)$$

where V_{ne} is the circuit voltage noise, V_{ni} is the circuit current noise, and V_{nr} is the resistance noise.

For this configuration with a large loop gain ($A\beta \gg 1$),

$$V_{ne} = e_n / \beta \quad ; \quad \beta = \frac{Z_{in}}{Z_{in} + Z_f}, \quad (2)$$

where A is the open loop gain, β is the feedback factor, e_n is the operational amplifier (op amp) voltage noise, and i_n is the op amp current noise.

Using the equations in (2) and circuit analysis and solving for V_{ne}

$$V_{ne} = \left\{ 1 + \frac{R_f}{[R_i - \omega^2 R_f C_f L]^2 + [\omega L + \omega R_i R_f C_f]^2} \right\} e_n \quad (3)$$

$$V_{ni} = i_n R_f \quad \text{for } R_f \gg R_i \quad (4)$$

$$V_{nr} = [4KTR_f B]^{1/2} \quad (5)$$

The values for this application are B (bandwidth) = 10 kHz, $K = 1.38 \times 10^{-23} \text{ J/}^\circ\text{K}$, $T = 290^\circ\text{K}$, $R_i C_f = 15.9 \mu\text{s}$, $\omega = 628 \text{ rad/s}$, and $R_i = 1.0 \Omega$.

Equations (4) and (5) illustrate the need to minimize R_f . However, R_f also determines the signal amplitude. Using Eqs. (1) through (5), the signal to noise ratio for this application can be determined.

$$\text{SNR} = \frac{\frac{\text{IBEAM}}{N} \times R_f}{V_{nt}} \quad (6)$$

Two op-amps were selected for evaluation, one for its low-voltage noise density ($e_n = 3 \text{ nV}/\sqrt{\text{Hz}}$ and $i_n = 0.6 \text{ pA}/\sqrt{\text{Hz}}$) and the other for its low-current noise density ($e_n = 11 \text{ nV}/\sqrt{\text{Hz}}$ and $i_n = 1 \text{ fA}/\sqrt{\text{Hz}}$). Using the preceding equations it was found that the op amp with the low-current noise required an excessive number of turns (1340) to maximize the SNR. Also the SNR did not equal 1 until IBEAM was 38 nA. The low-voltage noise op amp, on the other hand, provided a maximum at 184 turns. On this basis the voltage noise density was determined to be the dominant factor in the design of the I to V amplifier. See figure 6. It was decided that 200 turns would be a convenient number. With $N = 200$, $R_f = 50 \text{ k}\Omega$, $C_f = 330 \text{ pF}$, and $L = 8.0 \text{ H}$, an SNR of 1.04 could be achieved at 22 nA. The calculations indicated that, given the initial specifications, a design with approximately 20 nA minimum detectable current was possible.

Given the above constraints, one can see from figure 6 that any low frequency component in the input would swamp the signal at the output. Because the inductive reactance is small for these frequencies, the gain will be large as indicated by the following equation.

$$A = -Z_f/Z_{in} = -50 \text{ K}\Omega/1 \Omega = -50 \text{ K (DC gain)} \quad (7)$$

An additional amplifier feedback network reduced this effect. This network, combined with the original transresistance amplifier, serves as a band pass filter with 3 dB roll-off at 0.01 Hz and 11.1 kHz. The stability of this circuit is critical and can be controlled by the gain of the feedback network. Examination of the input stage lead to the feedback control model depicted in figure 7.

Figure 6 Current to Voltage Stage

Figure 7 First Stage Feedback Control Model

The open loop poles are at zero, $-1/(R_f C_f)$ and $-R_i/L$. The open loop transfer function is

$$G(s) H(s) = \frac{\frac{K}{C_f L R_x C_x}}{s(s + 1/(R_f C_f)) (s + R_i/L)} \quad (8)$$

The gain of the circuit is controlled by the voltage divider on the output of the feedback stage. The outer pole ($-1/R_f C_f$) has little effect on the inner poles.

The closed loop transfer function is

$$\frac{Y(s)}{X(s)} = \frac{G(s)}{1 + G(s)H(s)} = \frac{s[1/(C_f L)]}{s[s + 1/(R_f C_f)][s + (R_i/L)][K/(C_f L R_x C_x)]} \quad (9)$$

Using equation 9 and the following values a root locus plot (see figure 8) was generated.

$R_f = 50 \text{ k}\Omega$, $C_f = 330 \text{ pF}$, $R_x = 1 \text{ M}\Omega$, $C_x = 10 \text{ }\mu\text{F}$, $R_i = 1 \text{ }\Omega$, $L = 8 \text{ H}$

Figure 8 Root Locus Plot

Plotting the values of the poles as the feedback gain increases provides insight into the first stage stability. Using this information, Bode plots and the step input response for specific gains, the desired response and stability was determined.

The gated zero stage employs a different filtering technique. To attenuate frequencies below 200 Hz, the feedback network is gated so that the amplifier is zeroed during beam-off time. In this manner low frequency hum is reduced before the amplification stages. To minimize gating feedthrough, the gating circuitry is separated from the analog circuitry, both through ground isolation and physical location. See figure 9.

Figure 9 Gated Zero Stage

Following the gated zero stage are two stages of amplification. There are three output ranges, each with a full scale of 10 V. The output scale of these ranges is determined by the gain resistors selected in the amplification stages. Maximum measurable peak current, 40 mA, is determined by the current to voltage stage.

All components mentioned thus far are located within the current monitor chassis. The signals are then fed to an external chassis where there is another stage of auto zeroing and a final stage of signal conditioning can be used to eliminate noise outside the beam gate.

Mechanical Design

Early testing of the core and prototype amplifier showed coupling between the current monitor and local vibration sources. To evaluate the vibration isolation requirements, an analysis of the toroid and amplifier response to a variable-frequency audio signal was performed by attaching an accelerometer to the toroid. The amplifier showed a natural frequency of 180 Hz and the toroid resonance was at 550 Hz. The support structure was also analyzed. Forcing frequencies of 60 Hz were found in the structure. The prototype used pneumatic spring mounts attached to the outer cylinder to decouple vibration sources from the current monitor. Due to air leakage from the bellows, they were replaced by vertically supported springs and a means to adjust the amount of deflection. See figures 4 and 5.

Operation

An HSCM Display System provides real time analog signals and indication of average currents to the accelerator and injector control rooms. It also interfaces the HSCM to the accelerator binary control (RICE) and analog data (ADS) systems. See figure 10.

The desired gain range can be selected through the control computer. Selecting the range will automatically display and scale the computer readouts for that current monitor. The analog current signal is fed to the accelerator control room through a constant-current, line-driver receiver combination. This ensures that low-level signals generated at the current monitor are reproduced within 0.1% at the accelerator control room approximately one-half mile away. The signal serves as an input to an oscilloscope for on-line viewing of peak current and to a HSCM receiver. This receiver was initially developed for use in the Hardware Transmission Monitor (HWTM) system. The receiver integrates the signal and provides an indication of average current. The prototype HSCM required an averaging digital oscilloscope, but improvements in shielding the production unit eliminated this need.

The diagram illustrates the signal flow and power requirements for the Precision Receiver and Distribution system. Key components and connections include:

- TCCM1 Preamplifier Chassis:** Provides Low, Mid, and High gain signals to the Gain Select stage.
- Gain Select:** Receives binary select signals from RICE and local-comp data. It outputs signals to the Precision Driver and the ICR Gain Indication and Decimal Select.
- Precision Driver:** Receives signals from the Gain Select stage and outputs to the Precision Receiver and Distribution stage. It also receives power from the ±15V supply.
- Precision Receiver and Distribution:** Receives signals from the Precision Driver and outputs to Console A o-scope, Console B o-scope, Console C o-scope, and Peak Current to ADS. It also receives power from the ±15V supply.
- HWTM type Receiver:** Receives signals from the Precision Receiver and Distribution stage and outputs to Average Currents to ADS, Hardware Integrator and Chart Recorder, and Local DVM. It also receives power from the ±15V supply.
- Local DVM:** Receives signals from the HWTM type Receiver and outputs to Console C Remote DVM.
- Power Supplies:** ±15V and ±30V supplies are shown, providing power to the Precision Driver, Precision Receiver and Distribution, and HWTM type Receiver.

Duplicated for LXC3 and LCCM1

- 1) Selectable gains
 - a) Low 0 - 400 μ A peak @ 12% D.F. = 48.000 μ A average
 - b) Mid 0 - 40 μ A peak @ 12% D.F. = 4.8000 μ A average
 - c) High 0 - 4 μ A peak @ 12% D.F. = 0.4800 μ A average
- 2) Gain selection using the control computer or manually.
- 3) Automatic scaling of peak and average data.
- 4) Average current indication warning, if peak current analog channel saturates (>2000 counts).

Figure 10 HSCM Display System

Figure 11, showing the output of a chart recorder connected to the HSCM receiver output, illustrates a production P⁻ average current of 30 nA. A quiescent noise level of approximately 0.4 nA can be seen when beam is off. The differences in current magnitude, due to different states of injector operation, are indicated. Beam quenches, which are a means for measuring the beam polarization with the Lamb-Shift source, are also shown. The minimum reliable average-current measurement is 1 nA.

Figures 12 and 13 are photographs of the prototype HSCM output with a production P⁻ beam of 240 nA peak current. Circuit noise is approximately 100 mV or 40 nA. This is a factor of 2 greater than the calculated value. This may be due to the assumptions made in the calculations. Averaging the output signal over a number of pulses virtually eliminated all other noise components. Excellent results were obtained using 8 to 16 pulses. See figure 13. The photos illustrate that the averaging technique will allow one to determine peak currents to within the accuracy of the oscilloscope. The minimum reliable peak current measurement is approximately 50 nA.

Results from the production unit can be seen from a computer plot output from the LAMPF Analog Data System. See figure 14. Low energy transport (18 μ A peak) and experimental area (3.5 μ A peak) current monitors are displayed on the same pulse plot.

The peak and average current outputs of the HSCM are checked and calibrated once per year before accelerator startup. A precision current pulse is fed to a single calibrate winding through the current monitor. This simulates beam current. A single potentiometer in the HSCM receiver is adjusted as necessary. From past experience this adjustment has been minimal or not required. We have found, through experience, that the unit will provide accurate and reliable information.

The current monitor system was designed to minimize the requirement for recalibration when components of the system are replaced. Precision and high stability electronic components and system design specifications well within component limitations help to meet this constraint. The absolute accuracy of the electronics is $\pm 0.1\%$. Flux loss in the toroid (supermalloy) may contribute another 0.2 to 0.3%.

Figure 11 P- Average Current at Receiver Output

Figure 12 P- Beam 240 nA Peak, No Averaging

Figure 13 P- Beam 240 nA Peak, Average Equals 16

Figure 14 P- Beam 18 μ A and 3.5 μ A, Production Units

Conclusions

To assess the usefulness of the HSCM system, it is necessary to examine the benefits and drawbacks.

Benefits:

- 1) Accuracy and Linearity - The peak current outputs are accurate within 0.3% and linear over full scale of operation (10 volts).
- 2) High sensitivity - Signal to noise ratio is equal to 1 at peak current indication of 40 nA. Average currents can be measured to the 1 nA level.
- 3) Wide dynamic range - The device can accurately measure beam currents from 40 mA to 40 nA peak current.
- 4) Nonintercepting - The measurement of beam current will not interfere with accelerator operation.
- 5) High gain stability and reliability - Operation over the last 3 years has proved the unit can function reliably with instrument calibration performed once per year.
- 6) Energy independence - The accurate measurement of beam current is independent of the beam energy.
- 7) Vacuum - The current monitor is external to the vacuum pipe. This is convenient for maintenance and vacuum contamination considerations (outgassing).
- 8) Calibration - The current monitor is easily calibrated independent of beam operation.

Drawbacks:

- 1) AC device - Since the current monitor is an AC device, it will not measure neutral or DC beam currents. If H⁻ particles are stripped to H⁺, the current monitor will measure only the difference between the components.
- 2) Radiation damage - Since the electronics must be located as close as possible to the current transformer to minimize noise effects, they are exposed to ionizing radiation fields. This may cause the current monitor to fail due to radiation damage to the

electronics. However, this is not normally a problem since the currents we are interested in measuring are low intensity.

- 3) Bandwidth - The bandwidth of the unit has been limited for noise reduction.
- 4) Electrical isolation - To prevent measuring currents that flow along the beam pipe, an electrical isolation joint must be provided at one end of the current monitor.
- 5) Cost - Building a unit today the hardware would cost approximately \$20K to \$25K.

Over the past three years the HSCM system has become an integral part of the operation and problem diagnosis of the P- ion source. It is also used to calibrate other instrumentation in the P-experimental areas. It has met all specified design criteria except for an SNR equal to 1 at 20 nA peak; the present device has an SNR equal to 1 at 40 nA. This deviation is acceptable. For the applications at LAMPF the benefits far outweigh the drawbacks.

I thank Andrew Browman for the technical guidance he provided on the project design and implementation. Contributors to the mechanical design were Louis Morrison for the prototype and Edgar Bush for the production unit.

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