THE DEVELOPMENT OF A CURRENT MONITOR SYSTEM FOR MEASURING PULSED-BEAM CURRENT OVER A WIDE DYNAMIC RANGE*

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Abstract

This report documents the development of a current transformer system to measure pulsed ion beam currents at the LAMPF accelerator. Measured peak currents typically range from 100 nA to 30 mA with pulse widths varying from 30 μs to 1 ms. 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 ±0.1%. The system requires no operating adjustments and has proved stable and reliable during a year of operation.

Introduction

The Los Alamos Meson Physics Facility (LAMPF) presently operates three pulsed beam injectors, generating H^+, H^-, and polarized H^- (P^-) ion beams. Each injector is capable of variable pulse widths (typically 800 μs) and repetition rates (maximum frequency of 120 Hz). Typically the peak currents range from a few hundred nanoamperes for the the P^- injector to 30 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.

Nonintercepting current monitors are used to tune and operate the accelerator as well as to measure the beam currents delivered to 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 Monitor[1] (HWTM), which converts peak to average current and shuts off beam if a trip level is exceeded.

The present current monitor system is the latest in a sequence of evolving systems based on toroidal current transformers. The original installations were designed only for high-intensity beams, but the installation of the P^- injector provided the incentive to develop an accurate, reliable, nonintercepting current monitor that can measure both high- and low-intensity beams.

The desired response specified a 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 would provide 10 μV output from the initial stage. The major problem thus became minimizing the noise in the input stage.

Noise Minimization

Minimizing the noise while maximizing the signal-to-noise ratio (SNR) was the prime consideration in the development of this system. This was 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. Also the inductance must be 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. From past experience it was found that this is a good compromise between attenuating the high-frequency noise components and obtaining an analog output that is a meaningful pulsed representation of the input.
3. using filtering techniques and gating of the offset voltages to reduce the low-frequency noise.
4. selecting electronic components that have low voltage and current noise densities. Analog and digital circuitry were placed on separate printed circuit boards with individual power supplies to minimize gating feedthrough.
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.
6. shielding the toroid from electromagnetic fields with a Mu-metal can and a steel outer chassis. Microphonic noise was suppressed by decoupling the chassis from the beam-line support structure and placing a box lined with sound-absorptive material around it.

Physical Description

The toroid is a 2-mil Supermalloy tape-wound core (o.d. = 9 in., i.d. = 4 in., height = 4 in.) vacuum potted in epoxy and wound with 200 turns of 20-gauge copper magnet wire. The toroid core is epoxy vacuum potted to provide stabilization of the tape windings and dimensional definition. The toroid is encased in a Mu-metal shell to provide an electromagnetic (EM) shield. This canister-shaped shield has a slip-fit cover to allow installation and access to the toroid.

To optimize shield effectiveness the length of the canister was determined to be twice the diameter of the beam-line opening in the Mu-metal plus the toroid height. This shell is installed in a steel cylinder 14 in. long and 12 in. in diameter, with 0.5 in. thick walls. The cylinder, which has removable end plates, serves as the outer chassis. Three pneumatic shock supports provide the ground isolation and mechanical decoupling from the transport support and the beam line. The outer chassis sits within a cubic-shaped wooden structure, lined with sound-absorptive material, that functions as an anechoic chamber. The chamber has its own support and does not contact either the transport support or the beam line.

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The amplifier card, zeroing card, and the gating circuit are attached to the front and rear cover plates of the outer chassis. There are penetrations in the cover plates for the power and signal connections. An external NIM-bin chassis mounted on the transport structure houses the final stages of zeroing and signal conditioning (see Fig. 1).

Design

The primary design objective was to achieve a SNR equal to 1 with peak beam current, IBEAM, equal to 20 nA. The toroid was measured to have an inductance to turns-squared ratio (k_L) of 0.2 mH/turn^2. Therefore the inductance of the toroid (L) and the current into the initial stage of amplification (I_i) is given by

$L = k_L \times N^2$ and

I_i = IBEAM/N where N equals the number of turns.

Total noise[2] of the circuit (V_{nt}) is

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

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 ($A\beta >> 1$),

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

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.

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

$$V_{ni} = i_n R_f \quad \text{for} \quad R_f >> R_i \quad (3)$$

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

The values for this application are B (bandwidth) = 10 kHz, K = 1.38×10^{-23} J/°K, T = 290°K, $R_f C_f$ = 15.9 μs, ω = 628 rad/s, and R_i = 1.0 Ω.

Using Eqs. (1) through (4), one can determine the SNR for this application.

$$SNR = \frac{\frac{IBEAM}{N} \times R_f}{V_{nt}}$$

Two op-amps were selected and compared, one for its low-voltage density (e_n = 300 nV and i_n = 60 pA at 10 kHz) and the other for its low-current noise density (e_n = 1100 nV and i_n = 100 fA at 10 kHz). 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 Fig. 2). It was decided that 200 turns would be a convenient number. With N = 200, R_f = 50 kΩ, C_f = 330 pF, and L = 8.0 H, a 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. All the component requirements could be met with the exception of the toroid, where 200 turns produced an inductance of 7.7 H.

By examining Fig. 2 one can see 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.

$$A = -Z_f/Z_{in} = -50 \text{ K}\Omega/1 \; \Omega = -50 \text{ K}$$

To reduce this effect a feedback network was added to the amplifier. This network, combined with the original transresistance amplifier, serves as a band pass filter with 3 dB roll offs at 0.01 Hz and 11.1 kHz.

The next stage employs a different filtering

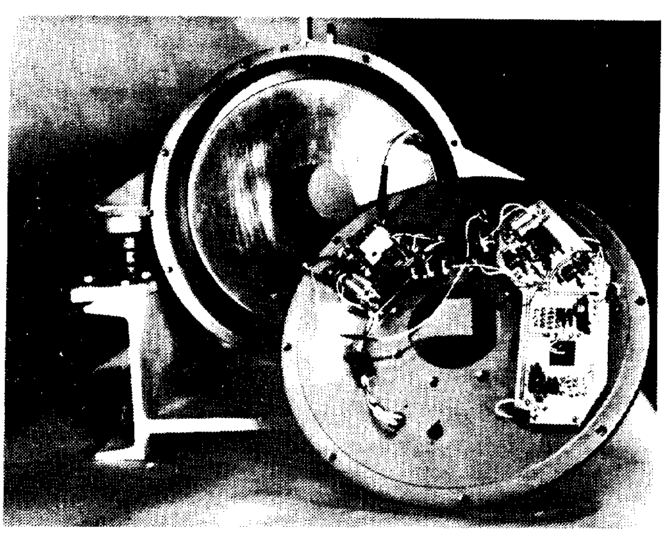

Fig. 1 Photo showing toroid, shielding, and amplifier electronics.

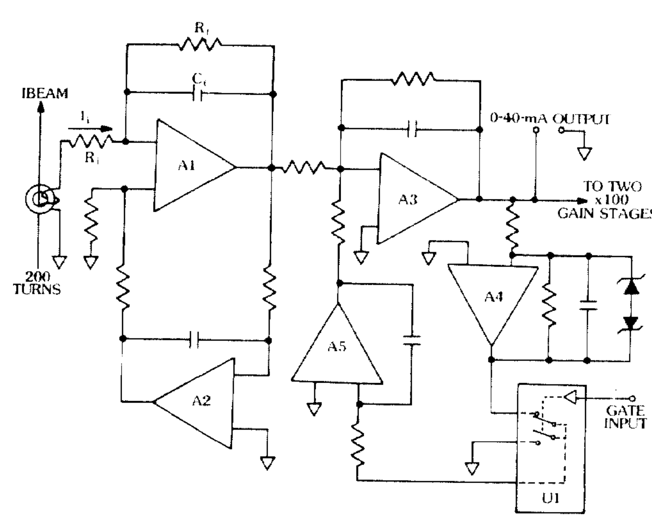

Fig. 2 Schematic of initial stages of amplifier.

technique. The feedback network is gated so that the amplifier in this stage is zeroed during beam-off time. This is necessary to attenuate frequencies below 200 Hz. In this manner one can reduce low-frequency hum before the amplification stages. The gating circuitry is separated from the analog circuitry, both through ground isolation and physical location. This minimizes any gating feedthrough.

Following the gated zero stage are two stages of amplification. There are three output ranges, each with a full scale of 10 V (0 to 40 mA, 0 to 400 µA, 0 to 4 µA).

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

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, whereas the toroid resonance was at 550 Hz. The support structure was also analyzed. Forcing frequencies of 60 Hz were found in the structure. Vibration decoupling of the current monitor from the support structure was accomplished with the use of pneumatic spring mounts attached to the outer cylinder.

Operation

Presently, only the 4-µA range 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 faithfully reproduced at the accelerator control room approximately one-half mile away. The signal serves as an input to an averaging digital oscilloscope and a Hardware Transmission Monitor (HWTM) receiver. The HWTM integrates the signal and provides an indication of average current.

Figure 3, showing the output of a chart recorder taking data from the HWTM, 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, are also shown. The minimum reliable average-current measurement is 1 nA (see Fig. 3).

Figures 4 and 5 are photographs of the output of the final stage of amplification 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. 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 Fig. 5). As the photos also illustrate, the averaging technique will allow one to determine peak-currents with considerable accuracy. The minimum reliable peak-current measurement is approximately 50 nA.

As the system is now configured, it provides both average and peak current information to be used as a diagnostic tool in tuning or as an indication of injector performance during normal operation.

References

1. A.A. Browman, "LAMPF Beam Transmission Monitor Systems," Proceeding of the 1981 Accelerator Conference, Washington, DC, March 11-13, 1981.
2. Ott, Henry W., Noise Reduction Techniques in Electronic Systems, John Wiley and Sons, Inc., 1976.

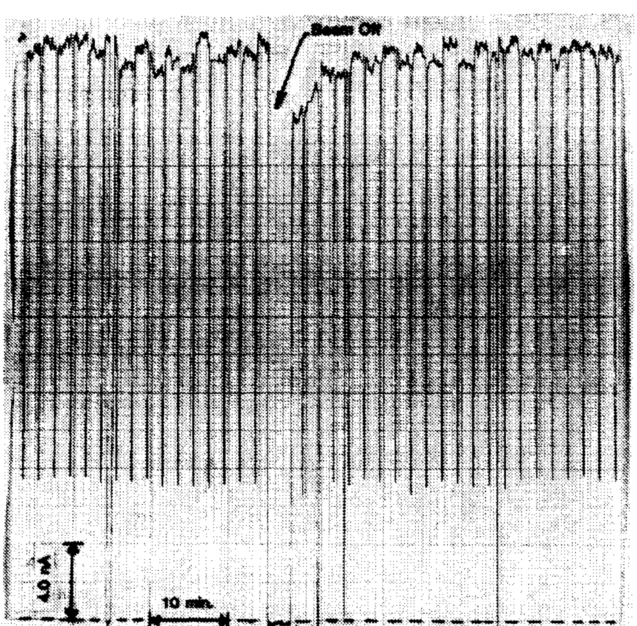

Fig. 3 P- Average Current at Output of HWTM.

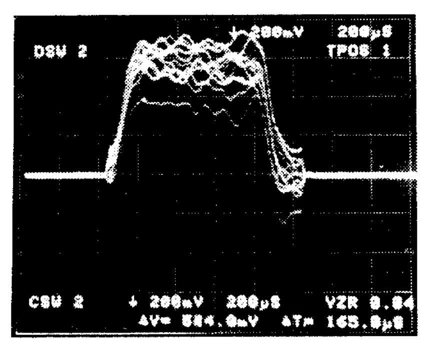

Fig. 4 P-Beam 240na Peak, No Averaging

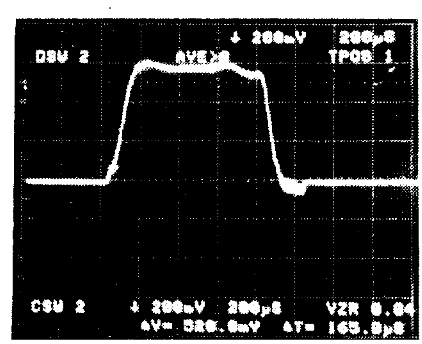

Fig. 5 P- Beam 240na Peak, Average Equals 8