IEEE Transactions on Nuclear Science, Vol. NS-26, No. 3, June 1979

30 μA BEAM TOROID*

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Abstract

A standard commercial toroid modified to operate in the zero flux mode has been applied to the monitoring of the 750 keV polarized proton beam at the Zero Gradient Synchrotron (ZGS). The beam parameters are: rise time - 3 ms, pulse width - 15 ms, current - 30 μA. This beam produces a free space flux of $H = 8.2 \times 10^{-7}$ oersted at the toroidal core radius. The device has a threshold of 10 μA as determined by system noise and operates with a bandpass of 10 Hz to 2.5 kHz. Ambient electromagnetic interference, predominately 30 Hz, 60 Hz and 200 MHz, was attenuated by use of a cylindrical "zero gauss" chamber. The addition of the magnetic shield introduced a sensitivity to mechanical vibration which was cured by isolation and stiffening.

Introduction

This paper describes the approach used at the ZGS for observation of the 750 keV polarized proton beam. The main features of the design are: the low frequency response may be sacrificed, a commercial toroid was used, a single high gain operational amplifier retrieved the signal, and a single layer 0.0039 m (0.052 in) magnetic shield adequately eliminated electromagnetic interference at 30 Hz, 60 Hz and 200 MHz.

The disadvantages are: the direct coupled stability is poor and the system bandwidth is much less than that of the signal.

Discussion

The toroid has an equivalent circuit shown in Fig. 1. Specified at 0.25 V/A sensitivity with a droop of 0.1%/μs, the base time constant is 1.22 ms in the presence of an infinite load. With the toroid output shorted, the time constant is 4.2 ms. At this time constant the high pass break frequency is 37.9 Hz. Figure 2 shows how the sensitivity of the toroid varies with load. With L_f open circuited, the system of Fig. 1 has a time constant of 3.4 ms. This calculates to an equivalent resistance of 5.7 Ω for the "virtual ground" of the amplifier. The resulting sensitivity from Fig. 2 is 0.028 V/A.

The amplifier is specified to have an open loop gain of 130 dB and broad band noise less than 0.3 μV/rms over a band of 10 Hz to 1 kHz. Considering the noise as constant with decreasing source resistance, the threshold input signal must be 0.3 μV. This corresponds to a toroid sensitivity of 0.01 V/A as the absolute minimum value for 30 μA of beam. Since the sensitivity is 0.028 V/A, we find a theoretical signal to noise ratio of 2.8:1 at 30 μA. The measured sensitivity of the open loop system is 7800 V/A indicating an amplifier gain of 2.8×10^5 (109 dB).

Closing the L_f feedback loop reduced the overall circuit gain and lowered the high pass break frequency. In this configuration the sensitivity is 1848 V/A indicating an overall gain of 6.6×10^4 (96.4 dB) with a time constant of 14.9 ms and a corresponding high pass break frequency of 10 Hz. The measured bandpass was 10 Hz to 2.5 kHz.

Noise sources, 60 Hz (line synchronous and asynchronous), 30 Hz (Rapid Cycling Synchrotron ring power supply), and 200 MHz (linac RF power amplifier) are tabulated below:

Source	Peak Output	Referred to H at Toroid
60 Hz	25 mV	3.8×10^{-7} oersted
30 Hz	75 mV	11.2×10^{-7} oersted
200 MHz	2.5 V	373.3×10^{-7} oersted

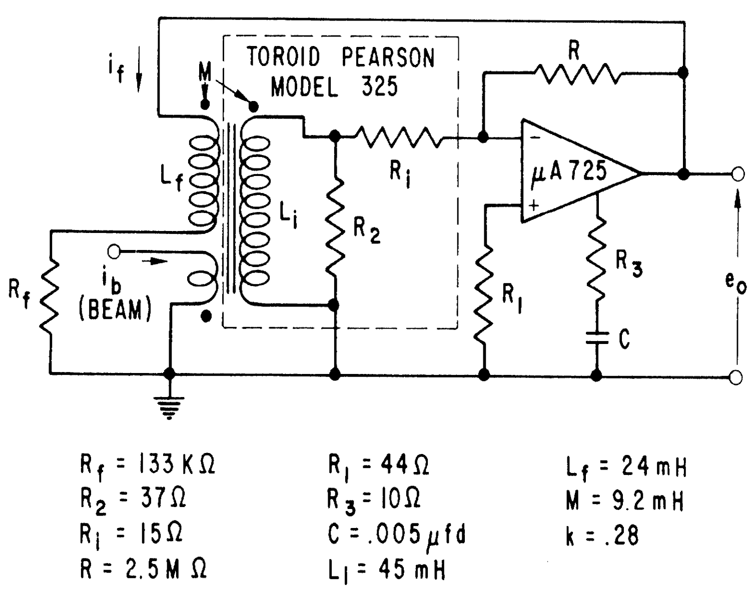

FIGURE 1
30 μA Beam Toroid System

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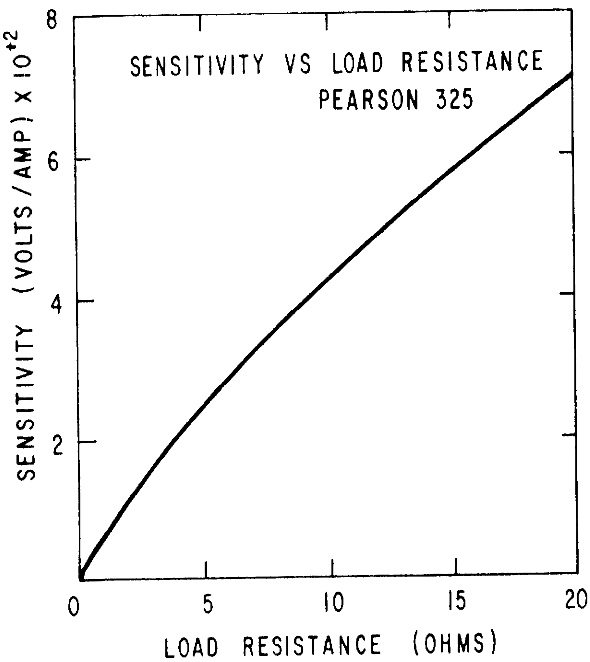

FIGURE 2
Toroid Loading Characteristic

In order to eliminate the low frequency noise a magnetic shield[1,2] was installed enclosing the toroid. This shield eliminated the direct electromagnetic coupling from all three of the sources cited on the preceding page. Unfortunately, it reintroduced the Rapid Cycling Synchrotron noise via earth transmitted vibrations. This noise was eliminated by isolating the chamber from ground with rubber pads and by insuring that the toroid and shield could not move with respect to each other. The ultimate noise with shield in place was the laboratory defined value of 20 mV peak to peak. This gave a measured signal to noise ratio of 2.7 to 1 at 30 μA of beam current.

Figure 3 shows a typical output from the system and compares it with a Faraday cup located 6 m downstream. The top trace displays the Faraday cup. The pip at the peak of the Faraday cup signal is the entire linac cycle. The sensitivity is 20 μA/division. The bottom trace is the toroid as viewed in the control room at a sensitivity of 50 mV/division or 1.85 mV/μA.

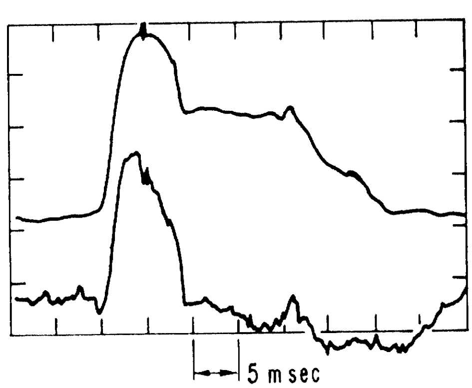

FIGURE 3
Toroid Calibration (tracing from photo)

The high gain configuration of Fig. 1 produced significant drift in the output dc level. This was expected and chopper stabilized amplifiers were tested in this application. The amplifiers tested introduced more high frequency noise than did the 725 and the degradation of the already minimal signal to noise ratio was less acceptable than was the drift.

Analysis of the circuit of Fig. 1 gives without approximations for the overdamped case with an input of $i_b = I \cdot U(t)$.

$$e_o = \frac{\alpha_2 I}{2}\left\{\left(1 - \frac{\alpha+u}{\beta}\right)\exp\left[(\beta-\alpha)t\right] + \left(1 + \frac{\alpha+u}{\beta}\right)\exp\left[-(\beta+\alpha)t\right]\right\} \quad (1)$$

with

$$\alpha_2 = A'R_A\left(M_b L_f - M_f M\right)\Big/\left(L_f L_i - M^2\right) \quad (2)$$

$$\beta = (\alpha^2 - p)^{1/2} \quad (3)$$

$$\alpha = n/2 \quad (4)$$

$$u = R_f M_b\Big/\left(M M_f - M_b L_f\right) \quad (5)$$

where

$$A' = 1\Big/\left(\frac{R_i}{AR} + \frac{R_i}{R} + \frac{1}{A}\right) \quad (6)$$

$$R_A = R_i\Big/\left(\frac{R_i}{R_2} + 1 - \frac{A'}{A}\right) \quad (7)$$

$$n = \left(\frac{R_f}{L_f} + \frac{R_A}{L_i} + \frac{A'R_A M}{L_i L_f}\right)\Big/\left(1 - \frac{M^2}{L_i L_f}\right) \quad (8)$$

$$p = R_f R_A\Big/\left(L_f L_i - M^2\right) \quad (9)$$

where M_f is the mutual inductance between the beam and the feedback winding L_f and M_b is the mutual inductance between the beam and the toroid winding L_i.

The feedback current i_f may be obtained from Eq. (1) by substituting α_1 for α_2, γ for u, and i_f for e_o in Eq. (1) with

$$\alpha_1 = \left(M_f L_i - M_b M\right)\Big/\left(L_f L_i - M^2\right) \quad (10)$$

$$\gamma = R_A\left(A'M_b + M_f\right)\Big/\left(M M_b - M_f L_i\right). \quad (11)$$

The term $\exp\left[-(\beta+\alpha)t\right]$ is zero for all practical t. This leaves $1/|\beta-\alpha|$ as the time constant for the closed loop system. $\beta-\alpha$ requires the difference between the two large numbers and may be approximated via the binominal expansion as

$$\beta-\alpha \approx -\frac{1}{2}\frac{p}{\alpha}\left(1+\frac{1}{4}\frac{p}{\alpha^2}+\frac{1}{8}\frac{p^2}{\alpha^4}\right). \qquad (12)$$

To a good approximation for Fig. 1,

$$\frac{1}{|\beta-\alpha|} = \frac{2\alpha}{p} = 13.2 \text{ ms} \qquad (13)$$

which is 11.4% low with respect to the measured value of 14.9 ms.

As an index to the literature on current transformers, the reader may refer to references 3 and 4.

Conclusion

Adequate detection of relative amplitude of a 15 ms wide 30 μA beam current pulse can be accomplished with an off the shelf toroid and a single amplifier.

References

1. S. M. Freake and T. L. Thorp, "Shielding of Low Magnetic Fields with Multiple Cylindrical Shells," Rev. Sci. Inst., Vol. 42, No. 10, pp.1411-1413, (Oct. 1971).

2. A. J. Mager, "Magnetic Shields," IEEE Trans. Magnetics, Vol. MAG-6, No. 1, pp. 67-74, (March 1970).

3. J. M. Anderson, "Wide Frequency Range Current Transformers," Rev. Sci. Inst., Vol. 42, No. 7, pp.915-926, (July 1971).

4. H. Feist, M. Koep and H. Reich, "A Current Transformer and Gated Integrator for Measurement of Weak Currents from Pulsed Accelerators," Nuclear Inst. and Methods 97, pp. 319-321, (1971).