Noninterrupting Method for Measuring Pulsed Charged Particle Beam Currents

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(Received 27 May 1963)

A noninterrupting method for measuring a charged particle beam current consisting of a series of periodic pulses is presented. The pulsed beam is allowed to pass through a high permeability toroid on which is wound a multiturn coil. If the distance traveled by a beam particle during one pulsing period is large compared with the toroid dimensions, then the voltage induced in the coil consists of a series of impulses, the time integral of each impulse being proportional to the beam current. Since this voltage is equal to that induced in the coil by a one-turn loop wound on the toroid and carrying a current identical to the beam current, it is possible to vary this current, and employ the multiturn coil as a null indicator to indicate equality of the beam and loop currents. If now a capacitor adjusted to resonate with the multiturn coil is placed across the coil, the sensitivity of the null circuit is increased by a factor equal to the Q of the resonant circuit. Using this resonant magnetometer and a 1000-cps chopping rate, currents of 3×10^{-7} A peak have been measured with an accuracy of $\pm10^{-8}$ A.

INTRODUCTION

CHARGED particle beams employed in atomic collisions research are normally measured by collecting the beam particles in a Faraday cup and measuring the resultant current from cup to ground. It is often desirable, however, to be able to obtain information about the beam current without physically interrupting the beam. Recent crossed-beam experiments, such as the one performed by Dolder *et al.*[1] on the ionization of He^+ ions by electron impact, require that one study the interactions resulting from the intersection of two beams which have been modulated (or chopped) to permit proper assessment of the reaction contributions due to background gas. In this paper we present a device which can be used to make noninterrupting measurements of such chopped charged particle beam currents.

The only previous reference to a noninterrupting beam current measurement appears to be a paper by Whitlock and Hilsum[2] in which an InSb Hall probe and null loop were used to measure a beam current with a magnetic field canceling technique. The smallest current which they reported detecting was 10^{-5} A. A substantial improvement in the sensitivity of their device appears to be quite difficult.

The device described in this paper utilizes the magnetic field produced by the chopped beam current to induce a voltage which is directly proportional to the beam current. This voltage is then compared to that produced by a known variable current in a single-turn nulling circuit. At the null, the unknown beam current is equal to the known null loop current. A description of the principles of operation of the device, followed by experimental procedures and results obtained, is presented in the following sections.

* Based on a thesis presented by W.C.L. in partial fulfillment of the requirements for the degree Master of Science in Electrical Engineering at the Georgia Institute of Technology.
[1] K. T. Dolder, M. F. A. Harrison, and P. C. Thonemann, Proc. Roy. Soc. (London) **A264**, 367 (1961).
[2] W. S. Whitlock and C. Hilsum, Nature **185**, 302 (1960).

PRINCIPLES OF OPERATION

This device is based on the fact that a chopped charged particle beam passing through a toroid on which is wound a coil induces in the coil a periodic series of voltage pulses, the time integral of a pulse being directly proportional to the beam current. This statement is valid provided that the distance that a beam particle travels during one chopping period is much greater than the toroid dimensions. This requirement is met in many cases of experimental interest; e.g., a 5-keV Li^+ beam, chopped at 1000 cps travels about 2×10^4 cm in one period, while a typical toroid radius might be 1 cm.

Subject to the above restriction, it becomes an easy matter to determine the first few terms of the Fourier series expansion of the series of voltage pulses, without requiring a detailed knowledge of the character of the individual pulses. Consider a chopped beam of peak current I_m amperes, pulse duration $\frac{1}{2}T$ sec, and period T sec. Allow this beam to pass through a toroid of mean radius R meters, cross-sectional area A square meters, and permeability $\mu_r\mu_0$ H/m. Assume for definiteness that a pulse is centered on the toroid at $\frac{3}{4}T$ sec. Then the fundamental frequency component of the voltage induced by the beam in an N-turn coil wound on the toroid is given by

$$V_f(t)=(2\mu_r\mu_0NAI_m/\pi RT)\cos(2\pi t/T). \qquad (1)$$

As a result of the particular time origin chosen, the coefficients of all of the sine terms are zero, as are the coefficients of the even harmonic cosine terms. The magnitudes of the remaining terms are equal to or less than that of the fundamental. It is important to note that Eq. (1) is valid even though the beam is not perfectly chopped. Equation (1) is also recognized to be the expression for the fundamental component of the voltage induced in the coil by a one-turn loop on the toroid carrying a square wave current of maximum value I_m, minimum value zero, and "in phase" with the beam current. If such a loop placed on the toroid produced a flux opposing that produced by

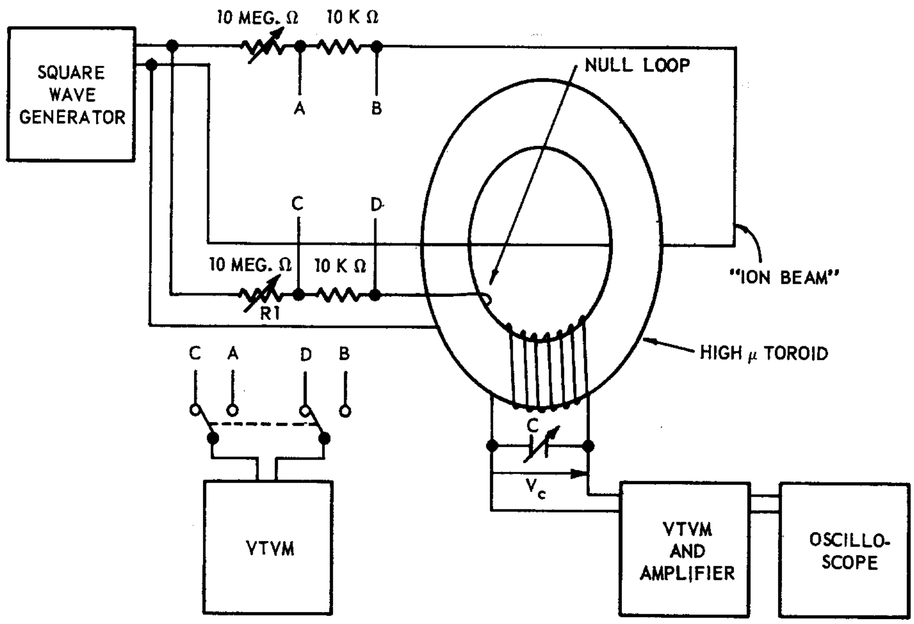

FIG. 1. Schematic diagram of noninterrupting beam current measurement apparatus with a wire simulating the pulsed beam. With capacitor C chosen to resonate the magnetometer at the beam chopping frequency, resistor R1 is adjusted for a null on the oscilloscope. The null loop current, which is now equal to the "beam" current, is determined by measuring V_{CD}. In this simulating experiment, V_{AB} serves to determine the accuracy of the measurement technique.

the beam, then the large coil could be used as a null detector to determine the beam current. Equality of the beam and wire currents produces cancellation of the fundamental component of the detector voltage.

The sensitivity of the detector may be increased and the effect of higher harmonics may be greatly reduced by placing a capacitor across the detector coil. Its capacitance is so chosen as to resonate with the inductance of the detector coil at $1/T$ cps. Under this condition the rms fundamental frequency component of the voltage across the capacitor is given by

$$V_c = \sqrt{2}\mu_r\mu_0 NAI_m Q_0/\pi RT, \qquad (2)$$

where Q_0 is the resonant Q of the detector circuit. For a high-Q circuit only the fundamental frequency component of V_c is significant.[3] Thus the addition of the capacitor increases the detection sensitivity by a factor Q_0 and eliminates all but the fundamental frequency component of the induced voltage. When the null loop current is equal to the beam current, the voltage appearing across the capacitor is zero. Thus the beam current may be determined by measuring the null loop current required to reduce V_c to zero. The use of a null loop provides beam current measurements which are independent of changes in the magnetic state of the toroid, and also eliminates the need for a calibration curve.

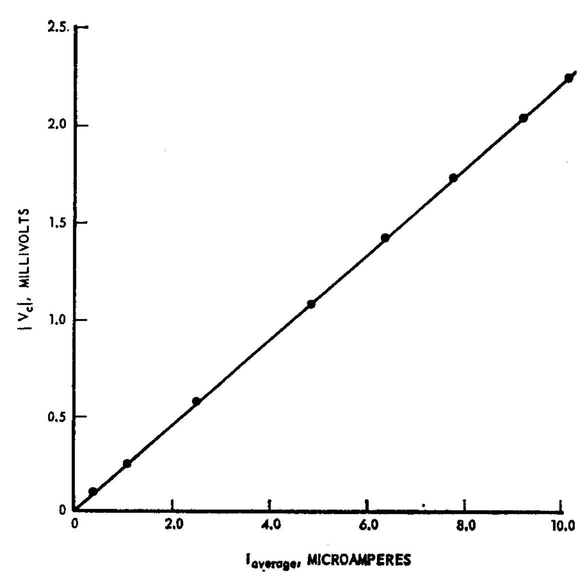

FIG. 2. Dependence of rms value of the magnetometer output voltage V_c on beam current with the null loop disconnected. The dependence is as predicted by Eq. (2).

EXPERIMENTAL PROCEDURES AND RESULTS

The preceding analysis shows that, for measurement purposes, the chopped beam and square wave wire currents are interchangeable. This result may be used to simplify an experimental investigation of the current measuring device. Initial investigations were therefore conducted with a "wire simulated" beam current, followed by tests with an actual electron beam.

Experiments Utilizing a Simulated Beam

Figure 1 is a schematic diagram of the simulated measurement apparatus. The "beam" current is determined by measuring V_{AB}, the null loop current by measuring V_{CD}. The characteristics of a typical magnetometer are $R=1$ cm, $\mu_r=250$, $A=1$ cm^2, and $N=600$ turns. This magnetometer resonates with a 0.1-μF capacitor at 2.35 kc.

The magnetometer was first operated with the null loop open-circuited. With the "beam" current flowing, the

[3] The first nonzero harmonic, the third, is smaller than $|V_c|$ by a factor of $1/9Q_0$. In general, if the kth harmonic is nonzero it is smaller than $|V_c|$ by a factor of at least $1/k^2Q_0$.

chopping frequency was adjusted to the magnetometer resonant frequency; this condition is accompanied by a sudden rise in voltage at the oscilloscope. The output voltage was then plotted as a function of "beam" current. Such a plot is shown in Fig. 2. The result corresponds closely to that predicted by Eq. (2). With the null loop reconnected, the unknown "beam" current is determined by adjusting the null currents for a null on the oscilloscope. Once the null has been obtained, the null loop current, and hence the beam current, is obtained by measuring V_{CD}. In this simulating measurement, V_{AB} serves to determine the accuracy of the noninterrupting measurement. With this particular magnetometer, the null could be easily obtained for $I_m = 3\times10^{-7}$ A. The accuracy of the measurement was $\pm10^{-8}$ A. The major source of error results from amplifier noise masking the exact location of the null.

Experiments Utilizing a Chopped Electron Beam

The experiment just described proves the validity of this measuring technique, provided the square wave wire current is equivalent to a chopped beam. Thus, a demonstration of this equivalence should be the object of any experiment dealing with an actual beam.

The work of Whitlock and Hilsum[2] offers one verification of this equivalence, since the authors successfully used a null loop technique to measure a chopped electron beam current. If the beam and null loop flux waves were not of very similar shape and magnitude, the null measurement could not have been successful.

In order to verify this equivalence further, a chopped electron beam experiment was performed by the authors. An electron source capable of producing beams with currents between 7.5 and 10 μA was utilized to obtain data for a plot like that shown in Fig. 2. The voltage induced in the measuring circuit by the chopped beam was the same as that induced by the square wave wire current. Null measurements were also successfully performed in this current range. When this verification is considered together with the work of Whitlock and Hilsum,[2] it appears that the experimental equivalence of beam and wire currents is well established.

The experiments described above were conducted with a beam duty cycle of 50%; however, it can easily be shown that other duty cycles yield equally valid results.[4]

DISCUSSION

This device as developed enables chopped beam current noninterrupting measurements to be conducted in the range of 10^{-7} A. This is nearly two orders of magnitude more sensitive than the device of Whitlock and Hilsum.[2] Increased sensitivity is attainable through the application of a more sensitive amplifier in the null loop and by the use of a higher Q circuit.

ACKNOWLEDGMENTS

The authors wish to acknowledge the interest and support of D. W. Martin and E. W. McDaniel throughout the prosecution of this work.

[4] W. C. Lineberger, Master's thesis, Georgia Institute of Technology, 1963, Appendix II.