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A WIDE BAND CURRENT MONITOR BASED ON PULSED TRANSFORMER TECHNIQUES

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June 1, 1973

Summary

A charged-particle beam current monitor has been designed using a coaxial cable transmission line in a configuration similar to that employed in building toroidal-wound wide band impedance matching and balun transformers. Several sizes of the coax-wound monitors have been constructed and compared with units of similar ferrite core material and geometry that were wound with ordinary magnet wire. One of the transformers has been used by experimenters at the NAL Internal Target area since August of 1972. In order to simplify electronic signal processing, only average circulating charge is measured. This is done by measuring the "zero"signal" baseline shift due to the natural L/R response of the transformer.

I Design

Many designs for measurement of particle accelerator beam intensities which use the beam of charged particles as the primary winding of a current transformer have been reported in the literature.[1] Most employ some configuration of toroidal windings with or without ferromagnetic enhancement and are either made resonant to some characteristic of the beam such as revolution or RF frequency or are made as wideband as possible. The NAL Main Ring has a particle revolution frequency of ∿21 μsec which changes ∿1% during an acceleration cycle, 80% of this change occurring between 8 GeV injection and 20 GeV transition energy. This also applies to the RF frequency. Resonant detectors were rejected, however, since the accelerator also operates in a multicycle injection mode, accepting from 1 to 12 1.6 μsec long proton bunches from the Booster and since future plans also call for debunching the beam during extraction.

In order to achieve a reasonable accuracy without investing in a prolonged development effort, a design goal was set of maintaining ∿1% absolute accuracy for a 1 to 5000 dynamic range in Main Ring beam intensity (10^{10} to 5 x 10^{13} protons). The only obstacle in achieving this large a dynamic range is maintaining adequate singal to noise margin at the low end. Since ferrite toroids are commonly used at high frequency, the lower frequency limit was of most concern. Specifically, it was required to have $\lesssim$1% droop over about 1 revolution, 21 μsec. Since it is necessary to operate the toroid at distances >100 feet from the signal processing electronics, a balanced line cable vice coax was selected. The cable, Belden type 8227 shielded-twisted pair, has a 100Ω nominal impedance and good high frequency characteristics for a twisted pair (4 db/100 ft at 100 mHz and 10 db/100 ft at 400 mHz). A toroid response with a droop of ∿1% in 21 μsec, using an R=100Ω and discounting the dc winding resistance, would then require an inductance of ∿210 mH.

*Operated by Universities Research Association Inc. under contract with the U.S. Atomic Energy Commission.

At one time Dr. A. Maschke† of NAL had suggested to the author that one should be able to wind a beam transformer with RG-174 coaxial cable in a way to eliminate electrical field effects. The concept suggested is similar to techniques using coaxial cable wound on toroids for constructing pulse, impedance matching, and balun transformers.[2,3] The results from a very quick comparison of two 15 turn transformers, one using #22 magnet wire and one using RG-174 indicated that a detailed comparison of two larger more carefully built transformers would be useful. Consequently, two 50 turn units and two 100 turn units have been built and tested.

II Construction

The ferrite core material, Ceramic Magnetics type MN-60, although not well-suited for this application, was used because the toroids were available at NAL. The initial permeability, μ_o, is essentially constant at low frequencies with a 3 db point at ∿600 kHz. Three of the toroids were cemented together under 200 lbs. pressure using Eastman 910 and yielding a toroid with physical properties described in Table I. The required number of turns for 210 mH inductance is then ∿100.

Table I

Outer diameter	23.3 cm
Inner diameter	17.4 cm
Axial length	7.8 cm
μ_o at freq. = 0	4800

The construction of the RG-174 coaxial version is shown in Figure 1. To wind the toroid two equal lengths of RG-174 were joined together by symmetrically cross-connecting braid and center conductor as shown. Fifty carefully spaced equal turns were wound in opposite directions until the ends came together diametrically opposite from the crossover joint. Here the two shields were joined and insulated and the two center conductors were then twisted tightly and brought out. This configuration presents an output impedance of 100Ω, a match for the 100Ω Belden twisted pair.

Since achieving the least possible signal-to-noise ratio for the low level toroid output signal was imperative, a rather elaborate shielding and support structure was built. See Figure 2. The outer magnetic shield is made of 1/4" cold rolled steel and is completely open on the inside facing the beam pipe. The inner, electrostatic, shield is electrically isolated from the magnetic shield which is grounded locally. A 1/4" gap is left on the inside of the electrostatic shield facing the beam pipe. The electrostatic shield is connected via an insulated feed-through triaxial connector to the shield of the 8227 cable.

III Testing

Bandwidth and sensitivity tests for

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Presented at the 1973 Particle Accelerator Conference

comparison of the toroids were made in the fully assembled housing, driving ∿240 feet of the 8227 cable terminated in 100Ω as required in actual use. This is essentially the input circuit shown in Figure 4, the electronics diagram. Considerable problems were experienced with the test set up because of impedence discontinuities at the shield gap where the toroids were located. The final set up used two 1 foot pieces of 6 inch diameter Main Ring beam pipe with a 1" gap, a wire down the center and a large piece of aluminum foil connecting the two pieces of pipe around the outside of the magnetic shield to complete the primary turn. If further tests are carried out, a 50 ohm impedance matched test fixture will be constructed.

Measured characteristics of the two toroids are given in Table II, and bandwidth curves in Figure 3. Prior to the tests it was expected that only the 100 turn outer shield was of significance in coupling to the primary and determining the self inductance. Since the data shows sensitivity down by a factor of 2

Table II

Parameter	#22 AWG	RG-174
# Turns	100	100
Ferrite Cores	MN-60	MN-60
Dimensions	See Table I	
DC Resistance	.48Ω	9.66Ω
Length of wire/turn	8.8"	9.2"
R with cable Z_o	100.48	109.7
No Shields:		
L measurement	234.5 mH	994 mH
Q	140	140
L/R = τ measured	2.38 msec	9.25 msec
L/R = τ computed	2.33 msec	9.06 msec
Mounted Inside Shields:		
L measurement	255 mH	1060 mH
Q	141	160
L/R = τ measured	2.37 msec	9.26 msec
L/R = τ computed	1.135 mV/mA	.55 mV/mA

for the coax wound toroid (scaled as 1/N turns) and self inductance up 4 times the magnet wire toroid (scaled as N^2 turns) one must conclude that both the shield and center conductor must be considered and we have effectively a 200 turn coil. Thus, if we decrease the number of turns in the coax wound toroid to 50, we should have a transformer which is comparable to the 100 turn magnet wire toroid but which also matches the impedance of the twisted pair transmission line. In fact, a 50 turn version was wound on a core of 1/3 the axial length of the test units and installed at the NAL Internal Target in August of 1972. It has been in steady use since that time and shows no evidence of deterioration due to radiation dosage. This was of high concern and a single test turn was installed as shown in Figure 1 to allow a regular sensitivity check.

IV Electronics

The quantity of charge circulating in the accelerator would normally be measured by integrating the current transformer's output with respect to time since the area under the waveform represents the total charge. Practically, this is difficult. Since the transformer is an ac coupled device, the "no proton" baseline will gradually be displaced away from the no signal baseline until charge equilibrium is established. To determine area under the curve electronically, the baseline would have to be dc restored; a process requiring sophisticated techniques to do fast and accurately, and justified only if the amount of total charge must be determined revolution by revolution. If an average measure of charge is acceptable, the following very simple technique can be used.[4] If I(t) represents the waveform produced by the current monitor and T is the period of revolution of a proton in the accelerator, then the total charge Q is the product of the amplitude of the baseline displacement times T, which by the Mean Value Theorem is equal to the integral of I(t) over T.

The electronics are shown in Figure 4. The differential input stage eliminated almost all common mode noise up to several megahertz. The second stage is a classical nonlinear feedback circuit, a precision rectifier in which the diode forward voltage is reduced by the open loop gain of the amplifier. Both amplifiers are Analog Devices AD48K's, which will probably be replaced by the faster AD46K's. The final stage, an active filter with gain, uses the very stable AD184J. Frequency response of the circuit is essentially constant from ∿10 kHz to 100 kHz. Some drop off above this was found and is determined by how fast the 2nd stage amplifier can dump charge into C_1. Some improvement was made by paralleling 3 of the HP2800 charging diodes leading to C_1.

V Conclusion

A new type of beam current transformer has been designed, tested, and operated. With present electronics, the desired 1% accuracy in measurement of average charge has been achieved over a dynamic range of 100 to 1 and an accuracy of <5% over a range of 1000 to 1.

Acknowledgements

The author would like to thank Dr. A. Maschke and Mr. Quentin Kerns for several valuable suggestions. D. Curl, R. Mirdas, and B. Rodewalt were of invaluable assistance in constructing and testing various pieces of the apparatus.

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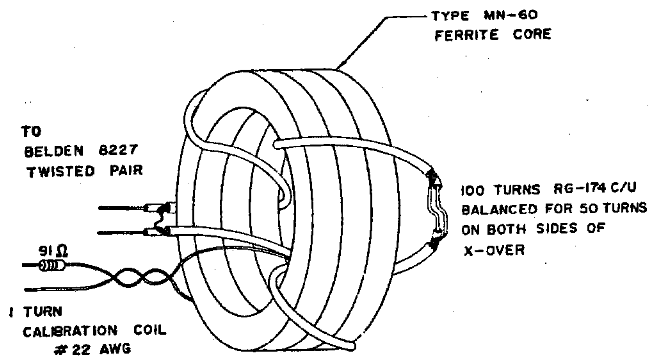

Figure 1 Construction of the Coaxial-Cable Wound Beam Current Transformer

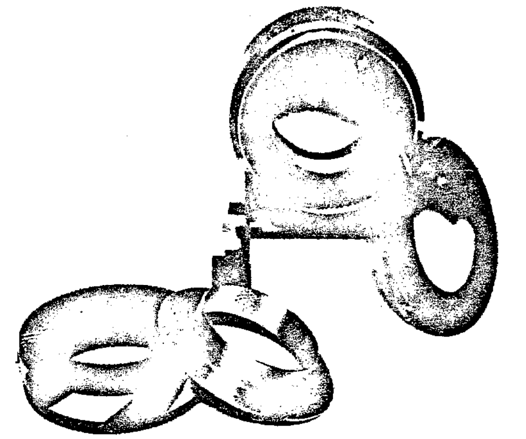

Figure 2 Current transformer Magnetic and Electrostatic Shields with the 100 turn coax Wound Toroid in Place.

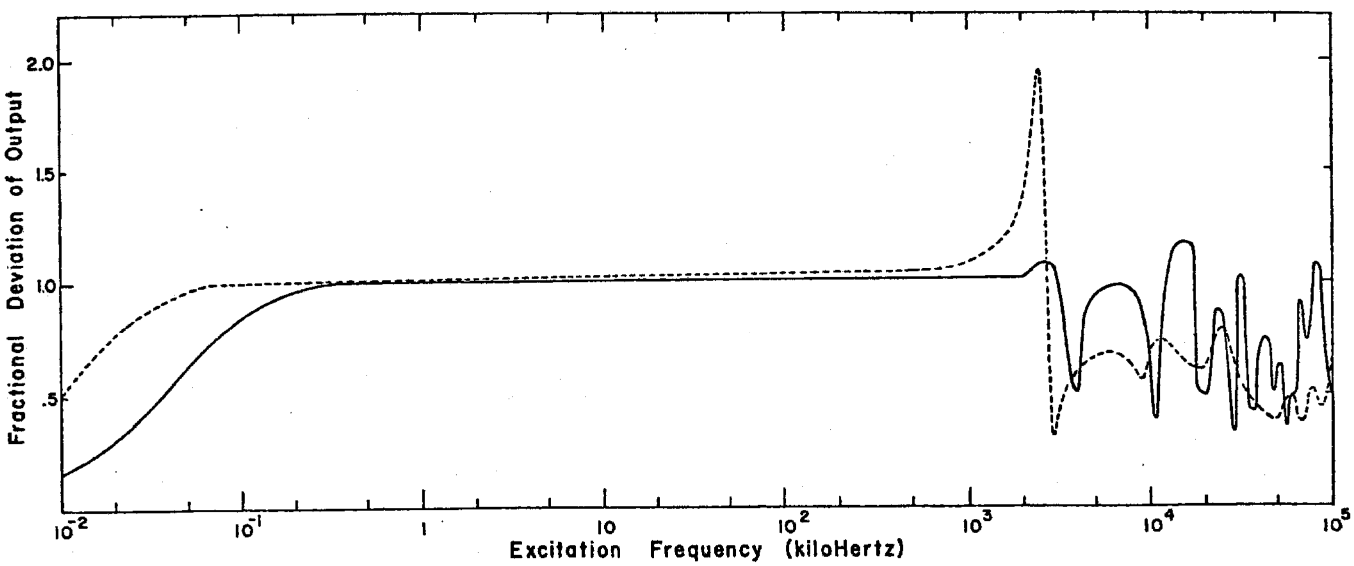

Figure 3 Frequency response of the Magnet Wire (solid line) and coax Cable (dashed line) toroids. The test set up was driven with a 2,0 volt peak to peak sine wave for all tests. The Fractional Deviation of Amplitude is computed by normalizing to measured amplitudes in the middle of the flat region - to 37.2 mV for the magnet wire toroid and 18.5 mV for the RG-174 toroid.

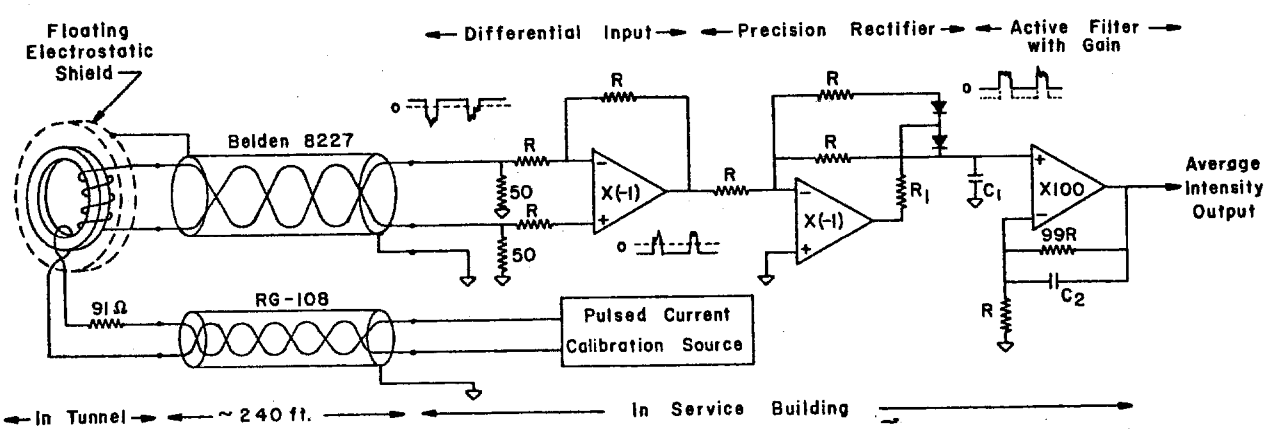

Figure 4 Electronics for measuring the average circulting proton beam current.