ISR-CO/69-6
March 1969

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

BEAM CURRENT TRANSFORMER WITH DC TO 200 MHz RANGE

by

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(Paper presented at 1969 Particle Accelerator Conference -
Washington D.C.)

Geneva - Switzerland

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Beam currents in particle accelerators are commonly measured by passing them through the center hole of a toroidal transformer. By definition, the response is limited to a.c. components of the signal.

The paper describes a combination of magnetic modulator and active L/R integrator in a common feedback loop whereby a current transformer with flat frequency response down to zero frequency is obtained. The scheme is analogous to the well known chopper stabilized d.c. amplifier and offers high accuracy and sensitivity, together with a large dynamic range and good zero stability.

The full frequency range from d.c. to more than 200 MHz is achieved by adding to this arrangement a fast passive current transformer with composite core and active back-up loop.

Introduction

The CERN Intersecting Storage Rings (ISR) will receive accelerated protons from the CERN Proton Synchrotron (PS). Bursts of about 10^{12} protons are injected once every second and successively stacked in an orbit. Each injected pulse consists of 20 bunches, a few nanoseconds long and spaced at 105 ns intervals. The current of the circulating beam in the storage ring will increase by 50 mA with each injected proton pulse and a circulating current of 20 A should be reached after a few hundred stacking cycles. This beam will be maintained in orbit for several hours.

The ISR circulating beam current monitor is required to determine injection and trapping efficiencies and to measure the total circulating beam current in the ring. Between successive injection cycles and after each completed stacking operation, the rate of decay of the stored beam must also be measured.

The ISR Circulating Beam Current Monitor

L/R integrator

The active L/R integrator with bifilar feedback and sensing winding (Fig. 1) was suggested by Hereward and is the basic operating principle of the circulating beam current monitor in the CERN Proton Synchrotron.[1,3]

This circuit can best be considered as a wide band current transformer (the beam signal acting as the primary turn) feeding into the summing point of a high gain feedback amplifier. The time constant and therefore the low frequency cut-off is improved by the factor (1 + A) compared to the passive transformer.

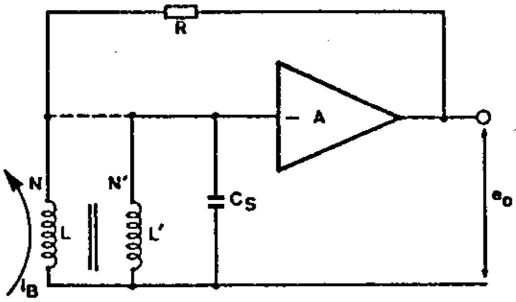


Fig. 1

For a high amplifier gain A, the circuit has the transfer function:

$$\frac{e_o}{i_B} = \frac{R}{N} \, \frac{1}{\frac{1}{pA\,L/R} + p\,\frac{C_S R}{A} + 1} \qquad (1)$$

p = Laplace variable

which reduces at mid-band frequencies to:

$$\frac{e_o}{i_B} = -\frac{R}{N} \qquad (2)$$

Periodic resetting is necessary to define the starting condition of the integration because the circuit as shown in Fig. 1 is not d.c. stable. To make it so, the magnetic modulator will be added.

The magnetic modulator

The transductor consists of a pair of toroids of high permeability material which are mounted together as shown schematically in Fig. 2. They are excited in opposite senses. Assuming both cores are identical, the voltages induced in a common sensing winding will cancel. A particle beam in the aperture of both toroids will introduce an assymetry and give an output of even harmonics of the modulation frequency at L_S.

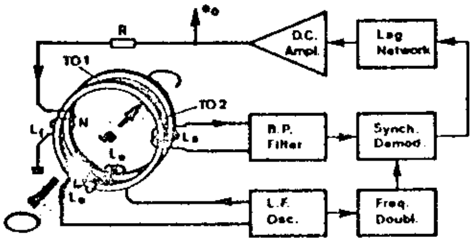


Fig. 2

The 2nd harmonic component of the output signal is proportional to the primary current and its phase determined by the direction of the beam.

A synchronous demodulator restores the d.c. signal. The lag network and a d.c. amplifier provide loop gain with controlled high frequency roll-off to obtain a stable feedback loop. This is not without problems, due to the limited linear range of the modulator. Assuming high loop gain, the transfer function of the configuration (at d.c.) is again:

$$\frac{e_o}{i_B} = -\frac{R}{N} \qquad (3)$$

The combined circuit

A simplified block diagram of the ISR circulating beam current monitor is shown in Fig. 3.

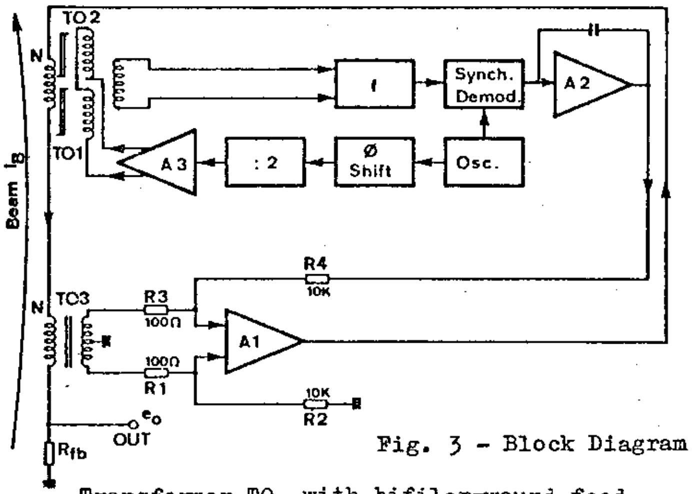


Fig. 3 - Block Diagram

Transformer TO_3 with bifilar-wound feedback and sensing windings, and operational amplifier A_1 are parts of the active L/R integrator circuit. The symmetrical input arrangement of amplifier A_1 and center-tapped sensing winding suppress common mode signals (e.g. capacitive pick-up and ionisation effects caused by stray protons[2]). The feedback current passes through windings with N turns on TO_1/TO_2 and on TO_3 and also through the feedback scaling resistor R_{fb}.

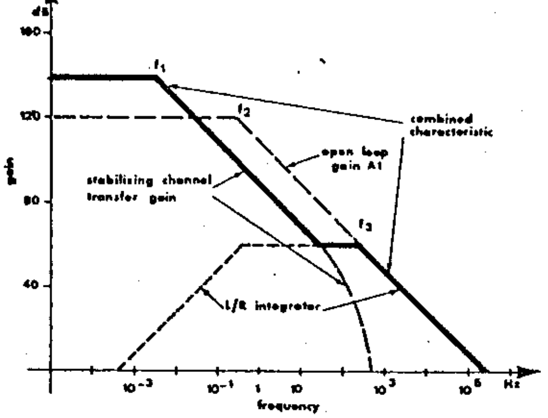
The 2nd harmonic modulator is similar to the schematic drawing in Fig. 2 and will see as an input signal any difference between the feedback current in R_{fb} multiplied by N, and the d.c. component of the beam. A d.c. correction signal will be applied to A_1 via amplifier A_2 and divider R_4/R_3.

The result is a d.c. drift stabilized current transformer whose operation resembles that of a chopper stabilized d.c. amplifier. By combining the L/R integrator and the 2nd harmonic modulator-demodulator, the advantages of both are realized and the shortcomings of each eliminated.

The combined circuit is unconditionally stable in the common closed loop configuration.

Amplifier and phase correction networks have been designed to yield the Bode plot shown in Fig. 4. The cross-over between the channels is determined by the transfer function f (L/R) of transformer TO_3 and feedback resistor R_{fb} in the L/R integrator loop.

Fig. 4 - Bode plot



Dynamic behaviour of the combined current transformer will mainly depend on the characteristics of the L/R integrator loop. Fast changes in beam current will not be seen by the 2nd harmonic modulator, but drift errors due to amplifier A_1 or the finite time constant of that loop are slow changes well within the slewing capabilities of the stabilizing channel. Momentary overload of the modulator is therefore excluded, provided the signal remains within the output current limits of amplifier A_1.

Excitation level control

The excitation level of the 2nd harmonic modulator is a critical parameter. The gain of the modulator-demodulator channel is continuously monitored by injecting a 20 Hz pilot tone in a similar way to the input signal. The magnitude of this signal at the output of amplifier A_3 is monitored by a phase-locked amplifier (not shown in Fig. 3). The slowly varying d.c. output of this amplifier is proportional to the transfer gain of the stabilizing channel and also indicates correct tracking of both channels. It controls the excitation level in the transductor and maintains the 2nd harmonic modulator in a state of optimum transfer gain. This also gives minimum zero error. When switching on, the control circuit will automatically apply maximum amplitude, driving both cores far into saturation to erase any residual remanence.

The pilot tone and modulator noise are suppressed by the L/R integrator loop and will not appear in the output signal of the monitor.

Prototype performance

A first prototype of the ISR beam current monitor (d.c. and medium frequency channel) has been tested. It uses one type of toroid for all functions, with a large inner diameter (200 mm) and a small cross-section (10 x 10 mm) to stay well clear of the vacuum chamber, which in the ISR must be baked out at high temperatures. The core material is Ultraperm 10[*] with 50 μm lamination thickness. All tests were performed with simulated beam signals. The results obtained, which are given below, are provisional, and should be improved by further development.

dynamic range: i_B = 1 mA to 20 A
transfer impedance: 1 ohm

Measured with 100 ms integrating time and expressed as equivalent beam current:

zero stability (long term): ± 1 mA

zero stability (10 min): ± 200 μA

accuracy: ± 0.02% ± 1 mA

Linearity errors and position sensitivity within the free aperture of the transformer are very small and completely masked by residual zero drift.

The device is in principle capable of fast response, but the primary objective is high accuracy at d.c. and low frequencies. The operational amplifier A_1 is designed for minimum noise in the low and medium frequency range and for an output current of 400 mA at 20 V. Consequently the maximum frequency for full power output is only about 40 KHz. Gain accuracy depends on the stability of feedback resistor R_{fb} (50 ohms) which has to dissipate 8W at the maximum rated output.

A fast responding current transformer is described in the following section. It is truly wide band and has a gain response down to d.c., but at reduced accuracy.

Wide Band Beam Current Transformer

In proton accelerators, high frequency information of beam current structure is usually available from capacitive pick-up stations. A fast responding wide band current transformer is useful in complementing this instrumentation, and will generally provide higher accuracy and more reliable measurements, especially under the condition of partial beam loss, e.g. at injection or ejection.

Response of a passive transformer

The proton beam has an ideal current source characteristic. Leakage inductance in the primary circuit of the beam current transformer will not affect the speed of response, and even a toroid transformer with a very large diameter is capable of risetimes in the ns range. The actual risetime is conditioned by the properties of the core material used and the structure of the winding. To limit the effect of stray capacities, a minimum number of turns of thin wire is used, evenly distributed over the whole circumference.

Many samples were tested in a special coaxial test rig (primary current step 4 mA with 0.5 ns risetime) in order to define the optimum design parameters.

Some typical results are shown in Fig. 5 and Fig. 6 with the sample transformers of Table 1.

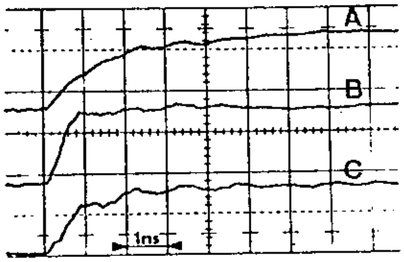


Fig. 5

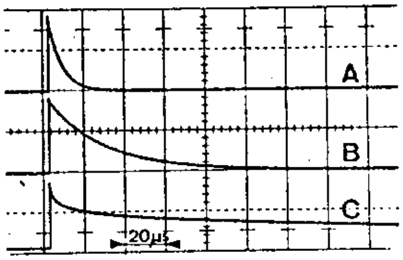


Fig. 6

Step Response of the Current Transformers in Table 1

Table 1 - Transformer characteristics
all with windings: 10 turns, wire ∅ 0.2 mm

Toroidal Core	A	B	C
material	Ferrite	Ultraperm 10	
lamination	-	10 μm	50 μm
μ_i	2800	24,000	80,000
dim. (mm)	150x92x25	170x130x25	180x130x25
L (100 Hz)	0.31 mH	1.6 mH	6.7 mH
L/R	6.2 μs	32 μs	134 μs

The tape wound cores with the high permeability alloy have a faster response than the ferrite core.

Eddy currents limit the penetration of the field at high frequencies limit to a very thin surface layer of the laminations in tape cores. The speed of response is not only a function of

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[*] Ultraperm 10, trade name for a 70 - 80% nickel-iron alloy (Vacuumschmelze AG, Germany).
μ_i = 80,000; μ_{max} = 300,000; B_{max} = 7,800 G

the thickness of lamination, and thus of eddy currents, but also of the spin relaxation times which are smaller in this material than in high permeability ferrites.

The permeability of tape wound cores depends on lamination thickness and reaches a maximum at 50 to 100 μm. This causes core C to have higher inductance, but also increased influence of eddy currents. Eddy currents are responsible for the abnormally fast initial decay (Fig. 6 - C) which is observed when the passive transformer time constant is less than 2 ms (for 50 μm lamination).

Cores with different lamination thickness may be combined in a single transformer. Risetime and initial decay during the first few microseconds will depend mainly on the core with the thinner lamination, while the core with the higher permeability will increase the effective time constant.

Active back-up circuit

A transformer of Table 1 has wide band response only when feeding a very low impedance. This reduces the voltage output and requires a linear amplifier of exceptional performance to lift the signal to a useful level. Such an amplifier degrades overall performance (risetime and signal-to-noise ratio) and has only a very limited dynamic range.

The L/R integrator of Fig. 1 is restricted in high frequency response by stray capacities C_S and by the slewing rate limit of the operational amplifier A. These problems are solved with a few modifications (Fig. 7).

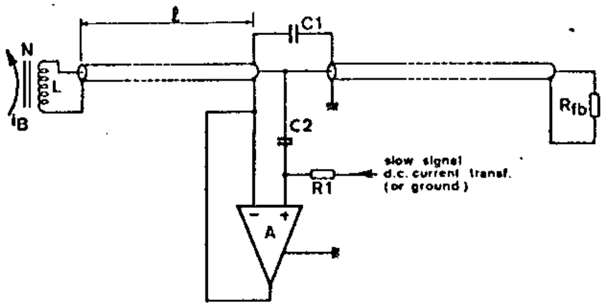

Fig. 7 - Active-Passive Current Transformer

By using a coaxial cable terminated by R_{fb}, the influence of C_S is largely eliminated. Fast transients from the transformer will feed directly into R_{fb} (forward feed), the ground return for high frequencies being provided by C_1, loading the output of amplifier A. The risetime of the passive transformer is fully conserved. The operational amplifier, limited by its finite unity gain frequency, will intervene progressively at lower frequencies, reducing the differential input signal to zero by forcing a current through L (and R_{fb}) to counter-balance the current i_B. This is just another way to see the action of the already familiar L/R - integrator in effecting an improvement in the low frequency response.

The operational amplifier is d.c. stabilized with R_1 C_2, a differentiation time constant which defines the lower cut-off frequency of the loop in the a.c. mode (R_1 grounded). One can also introduce, after appropriate scaling, the signal from the d.c. current transformer at the low end of R_1, providing response to d.c.

The circuit in Fig. 7 appears simple but presents a number of design problems which may only be mentioned briefly. The operational amplifier is required to supply large output currents and to drive a capacitive load. This condition is easier to obtain, at the relatively modest slewing rate required, than a comparable output level from a fast responding wide band amplifier.

The signal in R_{fb} (large amplitude with fast risetimes) is applied in common mode to amplifier A. The common mode rejection must exceed 40 to 60 dB over the entire frequency range.

The feedback amplifier presents a load impedance which rapidly decreases with frequency to a very low value. The coaxial cable between transformer and amplifier is therefore correctly terminated only over the frequency range of the passive response. This usually limits the length ℓ to a few meters, just sufficient to place the active components away from the beam and in a place where the radiation level is lower.

Performance

The active-passive beam current transformer is already in use in the CERN-PS-Linac to measure the intensity of the proton beam current pulse (duration 10 μs) down to very low current levels.[4] Trading off the increase in bandwidth for an increase in transfer impedance, by using a transformer with very few turns, a considerably improved signal-to-noise ratio and a large dynamic range are obtained.

A further circuit has been tested in the laboratory. It consists of an integrated operational amplifier (Motorola MC 1530) cascaded with a power booster. With a transformer of 10 turns made of a composite toroid, combining the cores B and C of Table 1, the transfer ratio is i_o = 1 V for a beam current of i_B = 200 mA (50 ohm load). This yields a risetime of about 1.7 ns with an upper frequency limit beyond 200 MHz. The circuit alone (R_1 grounded) has a lower cut-off frequency below 1 kHz (-3dB) and a useful dynamic range of 100 μA - 1 A equivalent beam current.

By injecting at R_1 the signal from the prototype d.c. current transformer (d.c. and medium frequency channels) true wide band response down to d.c. is obtained.

For the fast responding ISR-current transformer, the upper frequency limit is probably somewhat lower, because it requires a larger toroid (at present on order) and a large number of turns to cope with the high value of maximum beam current (20 A).

Other Applications

The new wide band d.c. current transformer is not limited to applications in storage rings. Already, at the present state of development the system has distinct advantages for measuring beam intensities in particle accelerators of the fast or slow cycling type. In such an aplication, response to d.c. is not considered a requirement, but the new system offers many operational advantages and higher accuracy.

Apart from beam observation there are many technical applications in the field of wide band precision current measurements (for example measuring the currents in beam transport magnets).

Tape wound cores of small dimension may be used as fast responding, wide band current sensors in electronic circuits. In the active-passive transformer circuit they yield a performance better than commercial current probes.[6,7,8]

Acknowledgements

The author is grateful to many members of ISR Controls Group who contributed to the project and the preparation of this report.

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