DESIGN AND PRELIMINARY TESTS OF A BEAM INTENSITY MONITOR FOR LEP

K. B. Unser
European Organisation for Nuclear Research (CERN)
LEP Division
CH-1211 Geneva 23, Switzerland

Abstract: The beam intensity monitor for the circulating beams in LEP uses toroidal cores of an amorphous magnetic alloy as sensors. It consists of two independent systems:

- A current transformer employing a parametric amplifying principle to measure the sum of the currents of both beams (dc component). This system has a resolution better than 0.2 μA and gives the absolute calibration of the monitor.

- A passive integrating current transformer to measure the relative charge of each individual bunch. Synchronous analog signal processing correct for baseline offsets and track a selected bunch over many revolutions. This permits to measure the number of circulating particles with great precision and for each bunch separately.

1. Introduction

The Large Electron-Positron collider (LEP) in CERN has a circumference of 26.7 km. The particles in each of the two colliding beams are concentrated in 4 regularly spaced circulating bunches, having a minimum rms length of 45 picoseconds and a nominal intensity of about 4×10^{11} e^+ or e^- per bunch. The peak value of beam current of these short bunches may be high (> 1 kA), but the mean value of beam current in LEP is rather low (≈ 0.75 mA per bunch).

A parametric dc current transformer is used to measure the total number of circulating particles in LEP. This intensity monitor does not require any timing information for proper operation and it provides a precise, absolute calibration without any ambiguity. The limitation of this system is its inability to distinguish between individual bunches. It measures simply the sum of the currents of both beams, even so they circulate in opposite directions.

A fast, integrating current transformer measures the charge of each individual bunch in LEP. The signal from this single transformer is used as an input for 8 parallel analog signal processing channels. Each of these channels is timed to track one particular bunch on every revolution and generates an output signal proportional to the number of particles in this bunch.

The limited space of this paper does not allow to treat both systems of the LEP beam intensity monitor completely. The following chapters will therefore concentrate on a selected number of novel features.

2. Magnetic cores made from amorphous alloys

High permeability alloys with amorphous structure have become commercially available in recent years. They exhibit exceptional magnetic properties, which makes them very attractive for beam current transformers. Their practical use in this context presents a number of technological problems. Different types of alloys are available and a preliminary investigation [12] selected Vitrovac 6025, with the composition $(CoFe)_{70}(MoSiB)_{30}$, made by Vacuumschmelze A.G. (Hanau, Fed. Rep. Germany). It is supplied in the form of a continuous ribbon of about 25 μm thickness, which is used to wind a toroidal core of any dimension. Compared with polycrystaline nickel/iron alloys, it has a higher permeability and lower eddy current losses (resistivity 2...3 times higher). One of the disadvantages of this material is a high level of magnetic noise (Barkhausen noise), a critical parameter for the application as magnetic modulators.

The amorphous structure is originally acquired by rapid quenching (cooling) at a rate of ≈ 10^6 K/s. The desired magnetic properties are obtained later by a thermal/magnetic annealing and relaxation process, below 500° C (recrystallization temperature). This has to be done with the material in its final core shape.

The magnetic cores for the beam current monitor have such specific requirements, that we had no choice but to learn to manufacture them ourselves. For a magnetic modulator with high resolution, we require an identical core pair with magnetic characteristics of exceptional stability, high permeability and a minimum of Barkhausen noise. A long series of systematic experiments permitted to set the following rules for the construction:

- a specially selected quality of Vitrovac 6025
- magnetic toroid free of internal constraints and freely "floating" inside a rigid support structure
- insulation between layers [11] without any defect, obtained with a Mylar foil of 1...2 μm thickness
- choice of geometry to avoid major magneto-mechanical resonances within modulator frequency range
- vacuum impregnation with a viscous damping fluid to reduce secondary resonances
- annealing for maximum permeability, minimum Barkhausen noise, best frequency response.

3. Magnetic field annealing

This chapter is a very simplified description of a rather complex subject. The annealing of the finished core consists of a controlled high temperature cycle in the presence of a magnetic field, which magnetizes the sample to the saturation level.

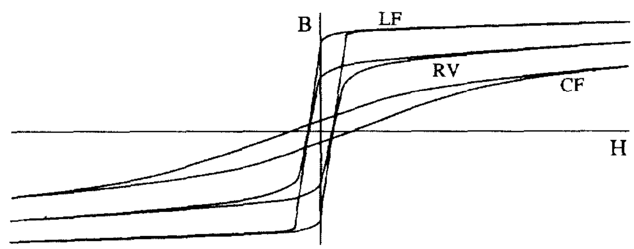

Fig. 1 Effect of annealing Vitrovac 6025.
Dynamic BH-curves at 100Hz

The field is most commonly applied in the longitudinal direction of the ribbon (LF). This produces a rectangular hysteresis loop (Fig. 1) with the highest value of max. permeability (≈ 500 000). The uniaxial anisotropy is at its maximum, leading to very large domain structures associated with a high level of Barkhausen noise and a relatively poor frequency response [9].

Cross-field annealing (CF) with the field perpendicular to the axis of the ribbon, yields a very flat BH curve with a much lower value of max. permeability (≈ 70 000), with improved frequency response. There are smaller magnetic domains and less Barkhausen noise than in the previous case.

It would be ideal in our application, to suppress the field induced anisotropy [10] and its associated macroscopic structures. Annealing without any field unfortunately does not work, because the magnetic domains tend to line up spontaneously in the axis of the ribbon, producing a situation analog to LF but with much lower permeability. There are methods reported [7], like heating above Curie temperature, followed by fast cooling (in water), or rotation of small samples in a stationary field. This is not a solution in our case, because the first method produces unstable magnetic characteristics and the second requires a very big magnet.

Our specially designed annealing plant permits simultaneous application of LF and CF. By suitable controls of the respective amplitudes, we are able to rotate the magnetic vector in a stationary sample. This type of processing is not easy to apply and at present certainly not yet optimized. It yields a hysteresis loop (RV) with the best dynamic properties.

4. The zero flux current transformer (ZFCT)

The basic operating principles of the zero flux current transformer has been described in two earlier papers [1; 6]. It consists basically of a toroidal current transformer and an operational amplifier, connected together in a closed feedback loop. The current to be measured (for example a particle beam) passes through the center of the toroid and is the single turn primary winding. The operational amplifier maintains the dynamic balance between primary and secondary current over a wide frequency range and particularly far down into the mHz region.

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tially controlled by the inductance L_1 and the core losses R_1, associated with core 1, and the equivalent load capacitance $n^2 C_L$. The load capacitance C_L (chip capacitors: 660 pF) is integrated directly into the winding of core 2.

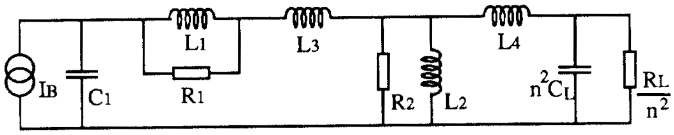

Fig. 5 Simplified equivalent circuit diagram of ICT

- I_B : beam current (current source)
- C_1 : storage capacitor of secondary loop
- C_L : storage capacitor of tertiary loop
- L_1 : inductance associated with core 1
- L_2 : inductance associated with core 2
- L_3 : leakage inductance in secondary loop
- L_4 : leakage inductance in tertiary loop
- R_1 : core losses of core 1
- R_2 : core losses of core 2
- R_L : load resistor (coaxial cable, 50 ohms)
- n : number of turns, winding of core 2 (10 ... 20)

The transfer function corresponds to a band pass filter, stretching the beam pulse signal by a factor of approximately 1000 (from 50 ps to 50 ns). This effectively lowers the frequency spectrum seen by the magnetic cores by a similar factor. The core losses under these conditions are small and the collected charge in the load resistor R_L is close to 100 % of the original charge of the beam pulse, divided by the turns ratio n. Cores with very small cross-sections can be used. The output signal is free from overshoot and ringing. It has always the same shape (the same frequency spectrum), independent of signal amplitude and bunch duration, providing that a certain design limit (1 ns) of bunch duration is not exceeded. The charge transfer ratio to R_L (calibration constant) is independent of bunch duration and beam position.

7. Fast analog signal processing

The bunch signal, after preconditioning in the ICT, is applied to 8 parallel analog signal processing channels. Each channel begins with a buffer amplifier, providing a low impedance source for 2 identical, fast analog gates (2 ns opening and closing time). These analog gates apply the same signal to either the positive or the negative input of a differential ac integrator. Each gate is only conductive during a short time interval t, for example 200 ns in LEP (60 ns for CESR). The gate to the negative input provides the sampling window t for one selected bunch in synchronism with the revolution frequency of LEP and the gate to the positive input samples the baseline immediately afterwards with a window t' of exactly identical duration. This symmetrical circuit arrangement restores the dc reference of the baseline, which has been lost by differentiation in the ICT. It provides not only the cancellation of the various known defects of fast analog gates, but is also a powerful method to reduce the influence of random input and amplifier noise.

The output signal of the integrator is proportional to the charge (number of particles) of the selected LEP bunch and averaged for a given number of revolutions.

8. First tests with beam

We had in autumn 1987 the opportunity, to install and test an early prototype of the LEP beam intensity monitor in CESR, thanks to an offer of collaboration from the Wilson Laboratory of Cornell University (Ithaca, N.Y., USA). The circumference of the e^+e^- collider ring CESR is about 35 times smaller than LEP, which scales up revolution frequency and beam currents in the same proportions. Minimum separation between bunches at the monitor location was 157 ns. This required modifications of the full scale range of the PTC, a shorter ICT time constant and an analog signal processor with a sampling time window of 60 ns.

8.1. Summery of test results:

PCT:

dynamic range:	+250 mA .... 0 .... -250mA	(single range)
tested with beam:	up to 130 mA	
resolution:	0.6 μA rms	(for 1 s integration time)

ICT+bunch signal prossesor
(for 60 ms integration time):

full scale (range A):	1.5×10^{11}	e
resolution (range A)	4.3×10^{5} rms	e
full scale (range B), estimated:	1.5×10^{12}	e
resolution (range B)	4.3×10^{6} rms	e
verified linear dynamic range (max. intensity during tests):	2.5×10^{11}	e
error for change of:		
beam position (±10 mm):	$< 1 \times 10^{-4}$	
bunch length (1.7 to 2.1 cm):	$< 3 \times 10^{-4}$	

attenuation of bunch signals outsite sampling window: -66 dB

9. Acknowledgements

Many people in the LEP-BI group, have made valuable contributions to the beam monitor project. P. Buksh designed the computer controled instrumentation for the dynamic testing of the core samples and did much of the measurements in the early phase of the project. A. Maurer and G. Burtin were of greatest help, whenever a professional mechanical engineer was required.

J. Bergoz and P. Pruvost (BERGOZ, Crozet, France) build the electronic units of the PCT (circuit diagrams furnished by CERN), constructed the annealing plant and manufactured a very large number of sample cores and transformer assemblies for the different tests. This work was done during 2 years in the framework of the collaboration contract K 017/LEP, free of charge to CERN in exchange for the transfer of technology and resulting commercial rights.

The tests at CESR would not have been possible without the active collaboration of M. Billing, R. Littauer, D. Rice and R.H. Sieman of Cornell University.

10. References

[1] K.B. Unser, "Beam current transformer with DC to 200 MHz range," IEEE Trans. Nucl. Sci., NS-16, pp.934-938, June 1969.
[2] "Current transformer for the ISR." CERN Courier, vol. 10, pp. 380-382, No. 12, 1970.
[3] "High precision DC beam current transformer with extended frequency range," CERN Technology Note B11, March 1974.
[4] M. Groenenboom, J. Lisser, " Accurate measurements of DC and AC by transformer," Electronics and Power, pp. 52-55, January 1977.
[5] H.C. Appelo, M. Groenenboom, J. Lisser, "The zero flux DC current transformer, a high precision wide-band device," IEEE Trans. Nucl. Sci., NS-24, pp. 1810-1811, June 1977.
[6] K.B. Unser, "A toroidal DC beam current transformer with high resolution," IEEE Trans. Nucl. Sci., NS-28, No. 3, pp. 2344-2346, June 1981.
[7] O. Komoto, H. Fujishima, T. Ojima, "Magnetic annealing of zero magnetostrictive amorphous alloy with high saturation induction," IEEE Trans. Magn., MAG-16 pp. 440-443, March 1980
[8] B. B. Narod, R. D. Russel, "Steady-state characteristics of the capacitively loaded flux gate sensor," IEEE Trans. Magn., MAG-20, No. 4, pp. 592-597, July 1984
[9] K. Shirae, "Noise in amorphous magnetic materials," IEEE Trans. Magn., MAG-20, No. 5, pp. 1299-1301, Sept. 1984
[10] V. Ungemach, W. Kunz, R. Hilsinger, "Influence of induced anisotropy on the magnetic properties of amorphous $Co_{66}Fe_4(Mo,Si,B)_{30}$ alloys," Journal of Magnetism and Magnetic Materials, 42, pp. 363-365, 1984
[11] D.M. Nathasingh, C.H. Smith, A. Datta, "Effects of coatings on the soft magnetic properties of an iron-based amorphous alloy" IEEE Trans. Magn., MAG-20, No. 5, September 1984
[12] H. Hundt,"Untersuchung der electromagnetischen Eigenschaften amorpher weichmagnetischer Metalle im Hinblick auf die Weiterentwicklung von DC-Strahltransformatoren,"Diplomarbeit, Fachhochschule Wiesbaden, Fed. Rep. Germany, January 1985
[13] K.B. Unser, "Toroidal AC and DC current transformers for beam intensity measurements," Atomenergie-Kerntechnik, vol. 47, pp. 48-52, No. 1, 1985

An auxiliary circuit with a magnetic modulator/demodulator, using a pair of toroidal modulator cores, senses the dc error between primary current and feedback current and corrects this error in the feedback loop. This maintains the main toroid (dynamic and static) at zero flux level and extends the frequency range to dc. The feedback current is measured with a precision resistor.

The ZFCT was originally developed as a beam current monitor for the ISR [2]. It is a good example of a specific accelerator technology [3], which has found a wide range of industrial applications [4]. It was this type of applications which did bring it back to the accelerators again [5; 13]. The trend is well illustrated in the LEP project, where more than 500 ZFCT's will be used for precision power control in conventional and cryogenic magnet systems and for monitoring the electrode and anode currents of the high power klystrons (security interlocks).

5. The parametric current transformer (PCT)

The parametric current transformer is a new step in the development of the ZFCT and has the same basic operating principle. It differs from the ZFCT in the electronic circuit concept. Important details concerning the excitation and demodulation circuits have changed and a parametric amplification scheme reduces the effect of amplifier noise.

The practical differences are a much higher modulation frequency and the use of magnetic cores with very small cross sections (in LEP: 5 mm^2; I.D. 210 mm). Circuits and interconnections have been simplified, without sacrificing performance. The PCT covers a frequency range from dc to 100 kHz and a dynamic range of 2×10^7 without range switching. The absolute resolution of the PCT depends only on the quality of the magnetic cores. Best performance so far obtained (with RV annealing) is < 0.2 µA rms (1 s integration window).

5.1. The modulator driver

The modulator excitation drive signal should be of very stable amplitude and frequency, completely free of even harmonic distortion. A square wave of perfect symmetry (≈ 7 kHz), is generated in a symmetrical D-MOS transistor bridge (Fig. 2). The amplitude is controlled by a precision dc regulator. The control signals to the switching transistors are derived by synchronous frequency dividers from a quartz controlled master clock.

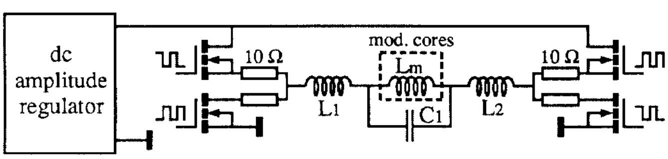

Fig. 2 schematic of modulator driver

The square wave driver supplies the excitation windings of the modulator cores via a symmetrical, passive low pass filter (L_1+L_2 and C_1). The value of capacitor C_1 is critical, because it is not only part of the LP-filter, but also the source of an avalanche current discharge into the excitation winding L_m, when the modulator cores approach saturation. This current can easily reach a peak of 4 A . Most of the energy initially stored in this capacitor may be recuperated. This requires an optimum choice of the resonance frequency, determined by the (changing) inductance of the modulator excitation winding L_m and the avalanche capacitor C_1.

The modulator driver of the PCT for LEP has a high efficiency. The absorbed dc power is less than 1 W for an excitation amplitude of 50 V and a peak current of 2 A into the modulator core windings. It has the simplicity of a square wave driver and provides the spectral purity and the high modulator sensitivity which is typical for sine wave excitation. The high value of peak saturation current is equivalent to an applied magnetic field of $H \approx 6$ A/cm in the modulator cores (500 times more than the minimum to reach saturation). This reduces Barkhausen noise and residual magnetic remanence (memory effect) and improves resolution and zero stability of the PCT in an important way.

5.2. Parametric amplification

Any magnetic modulator satisfies the definition of a parametric amplifier. The PCT uses a circuit arrangement to increase the sensor signal amplitude before it is applied to the transistor amplifier, thereby improving the signal to noise ratio.

Parametric amplification is commonly obtained in flux gate magnetometers, by loading the sense coil with a capacitor and tuning it to the second harmonic frequency [12]. The periodic permeability change of the flux gate cores provides the pumping action for parametric amplification. This principle cannot be applied directly to the PTC for two reasons:

- The sense coils are wound on a ring core (closed magnetic circuit) and have a low Q value
- Due to the very tight coupling between excitation and sense windings and any inevitable unbalance between the 2 cores of a modulator pair, the direct capacitive loading interferes with the avalanche circuit and may cause parasitic oscillations.

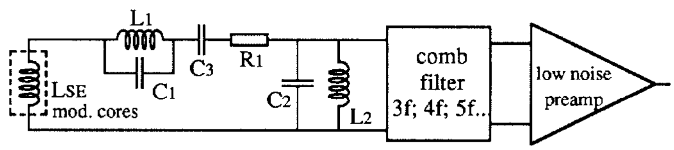

Fig. 3 Sensor signal conditioning circuits for the PCT.

Parametric gain is possible with the circuit in Fig. 3. A series and a parallel resonance circuit are connected to the sense windings L_{SE} of the magnetic modulator. L_1, C_1 is a band stop filter, tuned to the excitation frequency f. It attenuates the unwanted fundamental frequency components and eliminates interactions with the excitation circuit. L_{SE} is the source and the reactive load of the parallel resonance circuit (L_2, C_2) tuned to 2f. The parametric gain of this arrangement is adjusted with series capacitor C_3 and resistor R_1, which control respectively coupling and damping of the 2f resonance circuit.

6. The integrating current transformer (ICT)

Measuring the intensity of very short beam pulses (< 1 ns) with conventional beam current transformer is problematic. Core losses increase very rapidely with frequency and eddy currents limit the penetration of the magnetic field to a very thin surface layer of the magnetic material. One can use very thin magnetic ribbons (10 µm) and increase the core cross-section to compensate partially these effects, but the method is expensive and the calibration of such a current transformer is bunch-shape and beam position dependent.

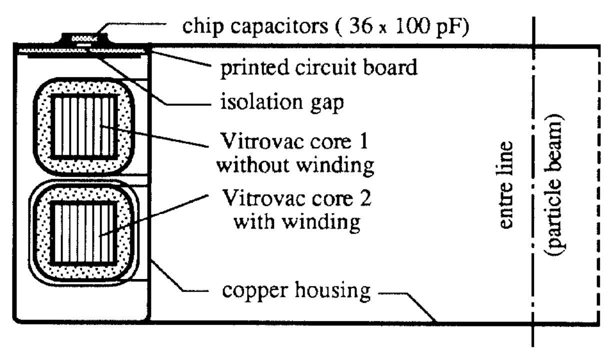

Fig 4. The integrating current transformer (cross-section)

A simple solution for this problem is the integrating current transformer (ICT) of the LEP bunch intensity monitor (Fig. 4). It contains two cores of Vitrovac 6025 (cross section 5 × 5 mm, I.D. 210 mm, magnetic ribbon of 25 µm thickness, RV-annealing). The two cores are completely surrounded by a toroidal copper housing. This housing is closed on one side with a ring shaped printed circuit board. The conductive pattern on this board form a coaxial capacitor of approximately 200 pF. Chip capacitors (36 × 100 pF) are soldered at regular intervals across a circular insulating gap and increase the total capacity to about 3800 pF. The toroidal enclosure with the coaxial capacitor form the single turn secondary winding of the current transformer. The beam passing through the centre of the toroid should be considered as the primary turn.

The charge induced by each short beam pulse I_B is temporarily stored in the coaxial capacitor C_1 (Fig. 5). This capacitor can only discharge through the single turn winding in the direction of the output load R_L. The rise and fall time of this discharge current is essen-