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Large Hadron Collider Project **LHC Project Report 720**

Wideband precision current transformer for the magnet current of the Beam Extraction kicker magnet of the Large Hadron Collider

E. Vossenberg, G. Gräwer

Abstract

The LHC beam extraction system is composed of 15 fast kicker magnets per beam to extract the particles in one turn of the collider and to safely dispose them on external absorbers. Each magnet is powered by a separate pulse generator. The generator produces a magnet current pulse with 3 μs rise time, 20 kA amplitude and 1.8 ms fall time, of which 90 μs are needed to dump the beam [1].

The beam extraction system requires a high level of reliability. To detect any change in the magnet current characteristics, which might indicate a slow degradation of the pulse generator, a high precision wideband current transformer will be installed. For redundancy reasons, the results obtained with this device will be cross-checked with a Rogowski coil, installed adjacent to the transformer.

A prototype transformer has been successfully tested at nominal current levels and showed satisfactory results compared with the output of a high frequency resistive coaxial shunt. The annular core of the ring type transformer is composed of a relatively low cost commercially available nano-crystalline strip material on an iron base. The characteristic feature of this material is a structure in which a fine-crystalline grain with an average diameter of 20 nm is embedded in an amorphous residual phase. This structure gives the material a high permeability. In addition, the small strip thickness (approx. 20 μm) and the relatively high electrical resistivity, result in extremely low eddy-current losses and excellent frequency behaviour. With a saturation flux density of 1.2 T this material becomes even superior to permalloys, ferrites or amorphous based alloys. In this particular application the transformer core is exposed to a unipolar induction. With normal magnetic materials this type of flux causes a relative high remanent induction. However this material allows controlling the magnetic properties, so called B-H curve shaping. It is obtained during annealing of the material by an external applied cross field and as a result the remanence ratio is less than 10%, which is excellent for this application. This paper presents the magnetic material, its incorporation in the design of the current transformer, comparative measurements of a prototype with a coaxial shunt precision resistor and explains why this device is an essential part of the LHC beam extraction system.

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WIDEBAND PRECISION CURRENT TRANSFORMER FOR THE MAGNET CURRENT OF THE BEAM EXTRACTION KICKER MAGNET OF THE LARGE HADRON COLLIDER

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I. INTRODUCTION

Figure 1 shows the entire length of the magnet current measured with the prototype current transformer and **Figure 2** shows the first 100 µs.

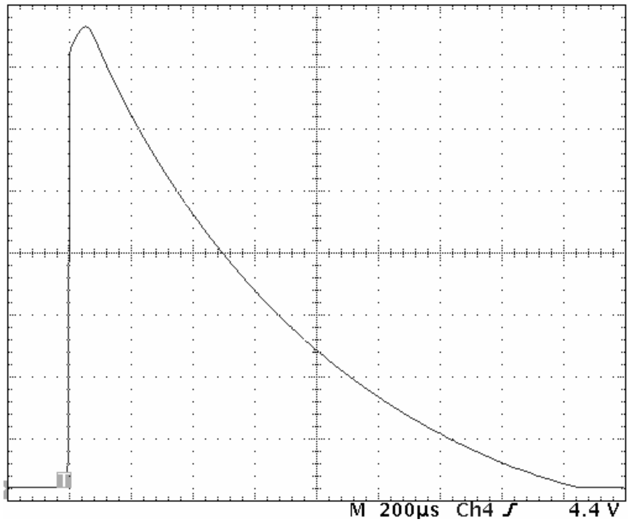

Figure 1. Entire length of the uni-polar magnet current.

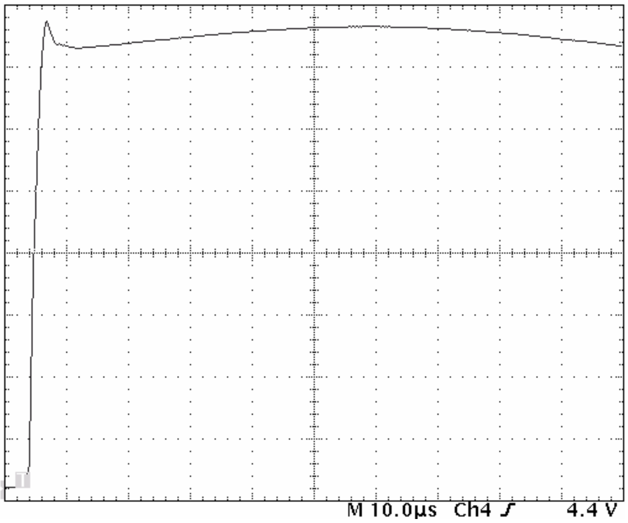

Figure 2. First 100 µs, including rise time of the magnet current.

Shielded pulse current transformers have been used to measure this type of magnet current for many years. These devices permit to determine currents without the need of direct electrical contact with the high voltage circuit to be measured and avoid ground currents with associated electrical noise. It also limits the insertion impedance in the circuit to a minimum. In this case the transformer has to measure pulse currents from about 1 kA to 20 kA with a 3 dB low frequency cut-off of 0.2 Hz and a 3 dB high frequency cut-off of 5 MHz with a maximum of 13 Amp-seconds. The conductor which carries the magnet current to be measured passes through the hole of the current monitor. In this case the return current of the magnet passes outside the transformer through a cylindrical housing. **Figure 3** shows the transformer and the cross-check Rogowski coil, make PEM® (UK), type CWT 150XB, in the housing. This cylindrical housing acts as a low inductive return conductor for the magnet current.

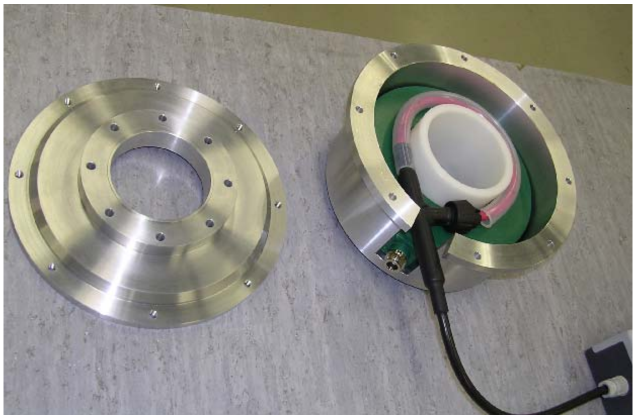

Figure 3. Current monitor and Rogowski coil in housing.

The performance of the current transformer is mainly governed by the properties of the magnetic material used in its construction. For this type of transformer a strip-wound toroidal structure is employed. Magnetic materials used in commercially available transformers include often grain orientated Si-Fe steel, Ni-Fe alloys or more recently amorphous iron alloys. Several attempts to use standard current transformers were unsuccessful. The major shortcoming of this type of transformers is the application of a gap in the core material. This gap is applied to increase the available flux swing in the core for a uni-polar pulse current. The result is a transformer with an increased current time product but still not enough ampere-second rating for a given core cross section. Another drawback is the too high droop rate for the first 100 µs caused by the not high enough permeability of the core material. Finally the output signal of these transformers appeared to be position sensitive due to external field penetration in the core gap. To cancel out these problems, an un-gapped core with nano-crystalline magnetic material was taken, because of its far superior magnetic characteristics and market availability.

II. REQUIREMENTS

The function of the LHC beam extraction system is to fast-extract the beam in a loss-free way from both rings of the LHC collider. Given the destructive power of the LHC beam, the beam extraction system must meet extremely high reliability criteria, which condition the overall and detailed design. A faulty beam extraction system could lead to severe damage to the beam dumping system itself, to the LHC machine or to the LHC experiments, due to full or partial loss of the beam onto machine components. It is therefore of high importance to measure the current in the extraction magnet very precisely and with a high level of reliability and to detect any slow degradation of the pulse generator. This implicates that the output signal of the magnet current transformer must measure the actual magnet current with a minimum of distortion. Given the limited mounting space available for the transformer and the cross-check Rogowski coil the cross-section and magnetic length of the core material are rather limited. On top of that it became clear that after the uni-polar magnetization of the core material, a magnetic core reset could not be included in the design. Nano-crystalline material was chosen with a saturation flux density of 1.2 T and very small remanent induction of 5%. The current transformer requirements are specified in **Table 1**.

Table 1. Current transformer specifications.

Dimensions	**mm**
Min. inside diameter	85
Max. outside diameter	158
Max. height	38
Input	
Max. peak current	20 kA
Max. Amp-seconds.	13
Rise time peak current	2.5 µs
Flat top peak current	100 µs
Fall time of current	1.6 ms
Pulse repetition rate	20 s
Output	
Output connector	N type
Max. usable rise time	100 ns
Output signal open	0.002 V/A
Output signal in 50Ω	0.001 V/A
Max. droop per ms	2%
Low freq. 3dB cut-off	0.2 Hz
High freq. 3dB cut-off	5 MHz
Accuracy	±0.5%

III. MAGNETIC MATERIAL

The precursor of nano-crystalline material is amorphous ribbon (non-crystalline) obtained by rapid quenching at about one million °C/second from a molten metal consisting of Fe, Si, B and small amounts of Cu and Nb. This material has good magnetic characteristics, such as low core losses. However when a heat treatment is applied for the toroidal core forming, the magnetic properties will decay tremendously due to rapid crystal growth (≈0.5 µm). It was discovered a few years ago that by adding certain alloy elements the crystal grains were extremely uniform and stayed during annealing very small in the order of ten nanometers. It turned out that these new nano-crystalline materials had excellent soft magnetic properties. As already mentioned this magnetic material is excellent as novel application for this type of current transformer. The major advantages are the high saturation flux density and permeability, which result in a significant reduction in size and weight of core material. The magnetostriction is very low, which means less mechanical core stresses. It has excellent high frequency characteristics, due to the thin ribbon (≈20 µm) and high electrical resistivity, which limits eddy currents. Finally by applying an external magnetic field during the annealing phase the shape of the B-H curve can be controlled. In this case an external field is applied perpendicular to the ribbon (magnetization) direction and a very low remanent ratio Br/Bs of 6% is obtained. This process is known as cross-field annealing.

A nano-crystalline cross field annealed core with low Br made by Vacuumschmelze® (Germany) was successfully tested at CERN. Type Vitroperm 500F, epoxy coated core model T60004-L2130-W587 was chosen with a core size of 134.5x95x28.5mm. Prototype transformers were purchased from Pearson® (USA) and Bergoz® (France). The Pearson device has been tested, Bergoz was not yet available for testing.

IV. TESTS

To test the core it was magnetically reset. **Figure 4** shows the flux plot of the core with saturation. It was confirmed that 1.2 T is at the end of the linear part of the B-H curve and µr is about 20000.

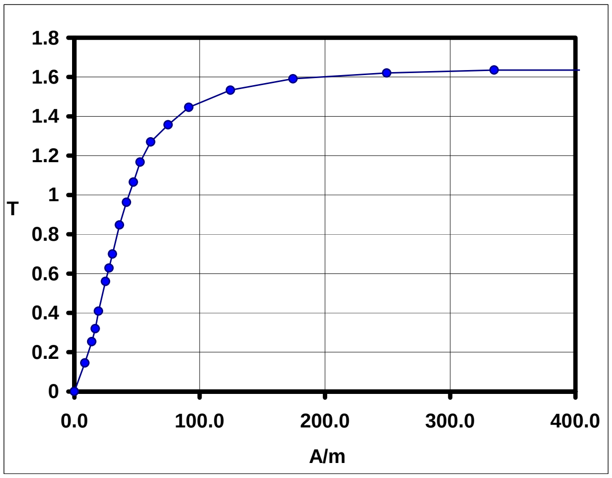

Figure 4. Flux plot of the core with Bs.

In the next test the core was again magnetically reset. Then a sinusoidal pulse current generated a maximum flux of 1.2 T in the core and the remanent flux was measured. The Br was about 0.07 T, which is about 6%. These figures correspond to the manufacturer's specification after cross field annealing.

Figure 5 shows the flux plot of the core with the remanent flux Br.

A test bench, shown in **Figure 6**, was made by CERN in order to evaluate the final transformer.

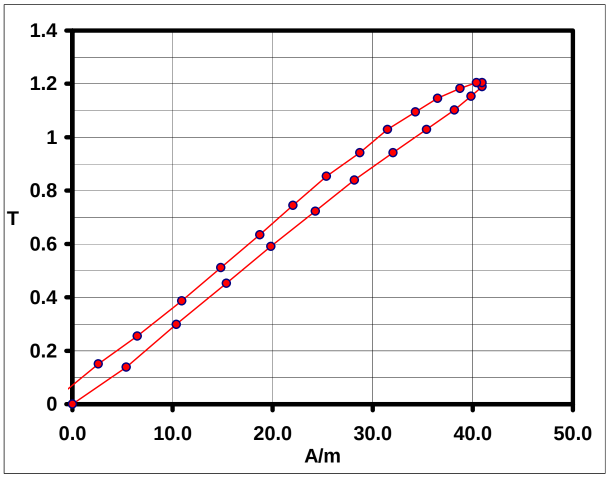

Figure 5. Flux plot of the core with Br of 0.07 T.

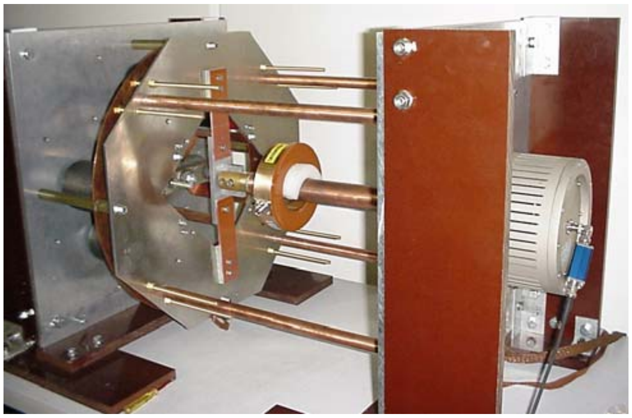

Figure 6. Test bench with coaxial shunt resistor.

The test bench consists of a charged capacitor, which is discharged by a fast high current thyristor into a series inductance and a 250 µΩ precision shunt resistor, make HILO-TEST®, type ISM 500. The inductance is formed by one central copper rod on which the transformer is mounted and four return bars as shown in **Figure 6**. After about 5 µs the current reaches its maximum and then decays through a free wheel diode. The current viewing resistor allows a very precise measurement of the peak value and waveform of the fast rise and slow fall of the current pulse. Because of its double coaxial design, the resistor is not susceptible to noise and electromagnetic interference. The maximum impulse-load integral of the shunt is far above the A²s of the actual current pulse. The usable rise time of the shunt is 7 ns and the bandwidth is 50 MHz.

The shunt output signal was taken as the reference and measured were the signal phase shift and signal difference during the rise time, overshoot at maximum current and during the fall time the droop rate, signal difference and ampere-seconds. To verify the dynamic range the measurements were carried out at 1800 A and at 22 kA. **Figure 7** shows the rise response of the transformer. **Figure 8** shows the first 170 µs of the current pulse and the relative error with respect to the shunt measurement is shown in **Figure 9**. Finally **Figure 10** shows the entire current decay. The output signals of the shunt resistor and transformer were measured with an oscilloscope. Considering that oscilloscopes have errors greater than 1% it is sufficient to have a transformer with less than 1% error or even less than 0.5% for most of the pulse length.

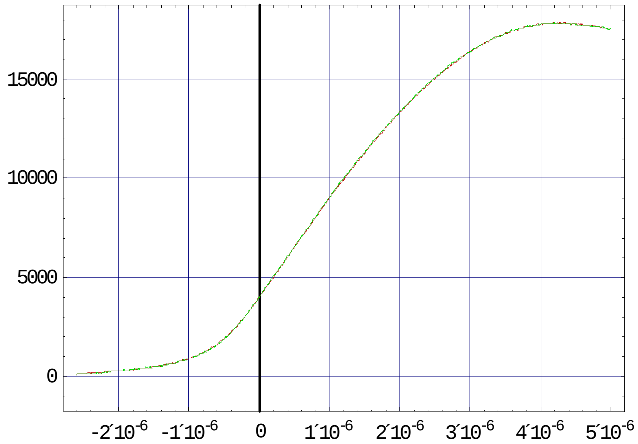

Figure 7. Rise time response of transformer compared with shunt signal.

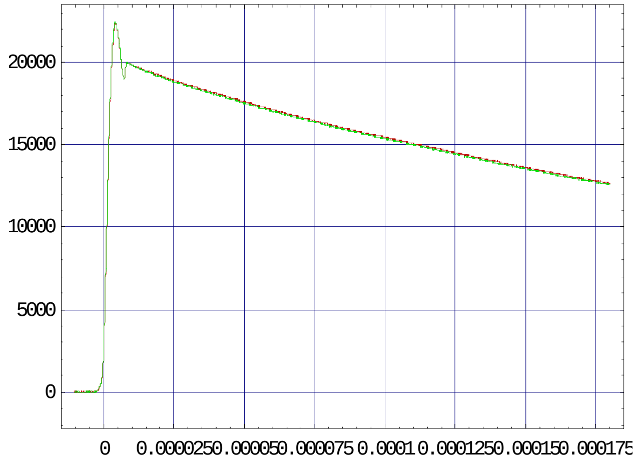

Figure 8. First 170 μs response of transformer compared with shunt signal.

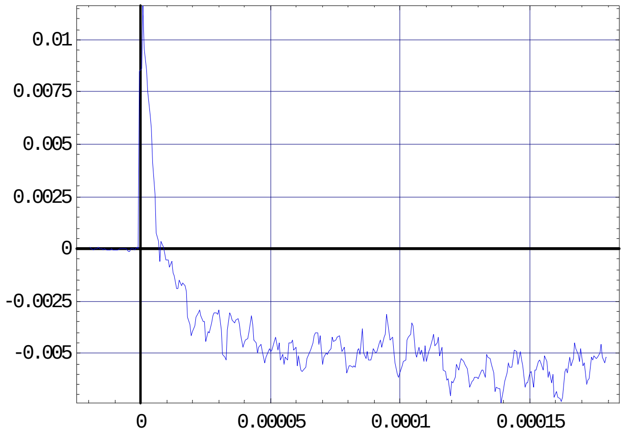

Figure 9. Relative error of the transformer during the first 170 μs response time.

V. RESULTS

This transformer has no significant phase error. The relative error during the rise time in **Figure 9** shows a large positive peak of 1%. This is caused by timing jitters of the oscilloscope and the fact that the signal is still so small that a given absolute error results in a much bigger relative error. The same figure shows an overshoot of approximately 0.5% that decays in less than 10 μs and settles to a relative error of less than -0.5%, which is the flat top error. The PEM Rogowski coil, type CWT150XT, showed an overshoot of nearly 1%. It then settled also to an error of less than -0.5%.

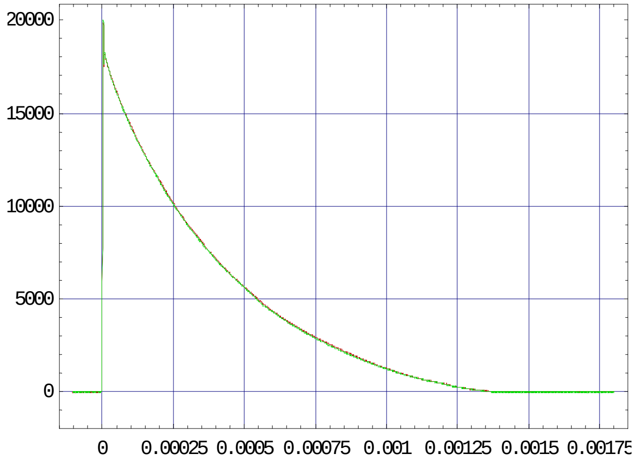

Figure 10. Transformer and shunt response during current fall time.

VI. CONCLUSIONS

The excellent soft magnetic properties of nano-crystalline material have triggered major interest and research activity in both the academic/research community and the industrial community.

The application of this material in current transformers and also in the cores of power distribution transformers will have a great cost and performance impact.

A transformer with the nano-crystalline core allows a precise measurement of the LHC beam extraction magnet current. Dynamic measurements show that the linearity of transformer is acceptable as is the long term stability. The transformer output signal will be used later in an automatic measurement for post mortem analysis. The aim is to measure the magnet current with an error of less than 0.1%. The output signal will be sampled with a fast digitizer. The transfer function of the transformer will be determined by measuring its output signal and the shunt reference signal on the test bench. With the calculated transfer function the sampled data will be corrected. This correction is not very critical since the error must only be reduced by a factor four to five.

VII. REFERENCES

[1] E.B. Vossenberg et al., "Dual Branch High Voltage Pulse Generator for the Beam Extraction of the Large Hadron Collider", Proc. 25th Int`l Power Modulator Symposium and 2002 High Voltage Workshop, 2002.