SYSTEM FOR LOCAL MAGNETIC FIELD MEASUREMENTS BASED ON A COIL WITH THREE SQUARE MILLIMETER

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Abstract

It is presented a system based on a mini coil with $3mm^2$ of section and 450 turns to measure local magnetic field. The structure of a coil is relatively simple, facilitating the evaluation of its sources of errors. The steps used to build the coil are shown as well as the performance of the measurement system. The calibration of the coil was made against a magnetic field generated by a Helmholtz coil with very well determined geometry.

INTRODUCTION

Faraday's Law is an empirical principle of electromagnetism which relates a magnetic flux variation inside of a closed circuit with an induced voltage (electromotive force). [1]

Mathematically, this induced voltage (V) is expressed by the derivative of the magnetic flux (Φ) with respect to the time (t):

$$V = -\frac{d\boldsymbol{\Phi}}{dt} \qquad (1)$$

where the negative sign is indicating that induced voltage tries to generate an electrical current which would hold the magnetic flux without variation (Len's Law).

The flux Φ is defined as the scalar product of magnetic field and surface vectors (Φ = $\boldsymbol{B.S}$). This flux variation can have two origins: mechanical movement of the conductive circuit changing its area or change of the magnetic field inside of the circuit. Equation (1) does not recognize the reason of the magnetic flux variation.

There are basically three conventional ways to measure the magnetic field with a coil:

1) Rotating the coil: this procedure is used to determine local fields, averaged in the coil surface. The voltage is induced by changing the flux in the circuit, due to angular variation between the field and the coil surface vectors. It allows to detect steady fields.

2) Displacing the coil: in order to measure a field profile, the coil scans continuously the region of interest. The field is obtained summing up the voltage induced in each step of the scan. This procedure does not detect steady fields.

3) Steady coil: it measures temporally variable magnetic fields.

Next sections will present what has been done to improve the applicability of the coils as a magnetic field sensor. The construction of a mini coil with 450 turns and its calibration, the description of the systems developed using this mini coil to measure as flip coil (rotating coil) and as displacing coil, as well as the preliminary results of both methods.

STATE OF THE ART

Probably, in a first analysis, the usage of this Faraday's principle is the most simple detection technique in terms of sensor manufacture, set of equipment and sensor intrinsic effects:

1) Sensor manufacture: any conductor loop can be a sensor. Anyhow, to measure small local fields, many turns are required since the induced voltage is very low and the usual electrical noises can mask it, what becomes a barrier for the coil miniaturization. To know the accuracy in the field it is necessary a precise coil area determination, what several times is not an easy task. A homogenous region of well determined field is useful to calibrate the effective sensitive coil area.

2) Set of equipment: Having a device capable to perform the voltage measurement, the magnetic field or its variation can be determined in a very direct way. In order to achieve a particular result it is required to evaluate the signal amplitude and compare it to the voltmeter resolution.

3) Sensor intrinsic effects: Due to principle explored to the magnetic field detection, the only expected effects are those related to the material of the turn. In this way, if the coil is made by a non magnetic conductor, the main effects will be mechanical expansion and electrical resistivity changes. Both effects are associated to variation of temperature (ΔT). The thermal linear expansion coefficient of the cupper is 1.7×10^{-5} / ^{0}C which brings a normalized variation $\Delta S/S$ equal to $3.4 \times 10^{-5}\ \Delta T$. And the copper electrical resistance (R) changes close to room temperature as $\Delta R/R = 0.0039\Delta T$. In general, it is negligible when compared to the voltmeter impedance (megaohms).

The biggest difficulty of this measurement system is the low amplitude of the induced voltage. To get 1 volt in the coil terminals it is required 1 tesla.m^2/ s. Both tesla and m^2 are big units when compared to desired field precision (1μtesla) in a region of 1 mm^2 (especially for local fields). Either for rotating coil or displacing coil, the time associated is in the order of tenths or hundredths of second. So, the solutions found to compensate such difficulties are to increase the number of turns and the motion speeds, to use high precision voltmeter and to reduce the electrical noise.

THE MINI COIL

A new system with small winding steps, small wire strength, low velocity and attached microscope to see the wire accommodation was designed to make the mini coil.

The copper wire used had 40 µm of diameter (47 AWG). Figure 1 shows the picture of a mini coil.

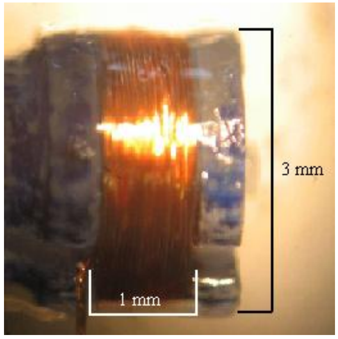

Figure 1: Picture showing a coil with 450 turns and its main dimensions.

Due to the large number of turns it was not possible to determine the coil effective area only by geometric considerations. To do this, the mini coil was assembled in the rotating coil configuration (next section) and placed inside of a well known and homogeneous magnetic field generated by Helmholtz coils.

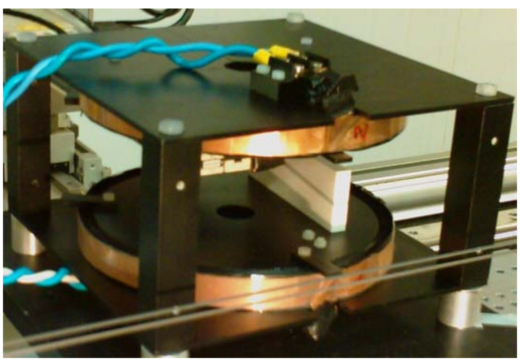

Figure 2: Picture showing a Helmholtz coils for homogenous and well known magnetic field generation.

Table 1: Mini coil main features

Inner diameter [mm]	1
Outer diameter [mm]	3
Number of turns	450
Insulated wire diameter [mm]	0.047
Effective area [mm2]	1414
Magnetic field precision [µ tesla] Flip coil	35
Magnetic field precision [µ tesla] Scan coil	35
Voltmeter precision [V]	1×10^{-8}
Resistance [Ω]	53
Inductance [mH] in 1kHz	0.26

MEASUREMENT SYSTEMS

Rotating Coil

This technique is used to determine the average magnetic field inside the coil, rotating the mini coil inside a steady magnetic field and measuring the induced voltage with a high precision voltmeter (Agilent 3458A). [2, 3]

The conversion of the induced voltage in magnetic field assumes that the measured signal has senoidal behaviour and the frequency (*f*) is defined by the rotating velocity of the coil (*f* = 1 Hz). Then, a perfect senoidal function (V) with the same frequency is adjusted over the measured voltage to determine the signal amplitude (V_A):

$$V = V_0 + V_A \sin(2\pi t + \psi) \qquad (2)$$

where V_0 is the voltmeter offset, β is the amplitude, ψ is the phase and *t* is the variable.

Since the amplitude of the measured signal is well determined after the senoidal adjust, the field can be found integrating the sinusoidal term over 1/4 turn:

$$B = \frac{V_A}{NS} \int_0^{1/4f} \sin(2\pi t)\, dt \qquad (3)$$

where B is the magnetic field and S is the mini coil area and N the number of turns.

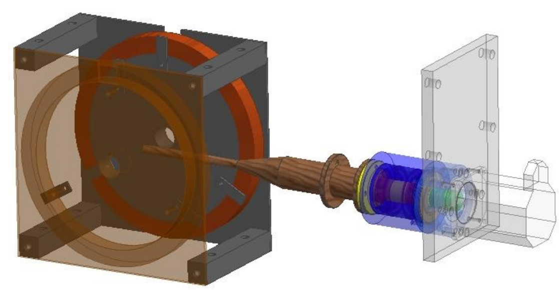

Figure 3: Draw of the rotating mini coil system.

Scan Coil

The scan coil is designed to measure magnetic field profiles. The mini coil is fixed in a support with a Sentron hall probe and both move in the magnet field to be determined (Figure 4). The field detection was tested measuring an undulator subcassette (Figure 5). Since the magnetic flux changes inside the mini coil during the scan, the induced voltage can be measured with the voltmeter (Agilent 3458A).

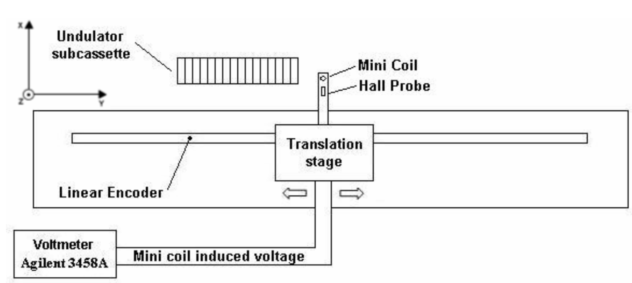

Figure 4: Schematic drawing for scan coil measurements.

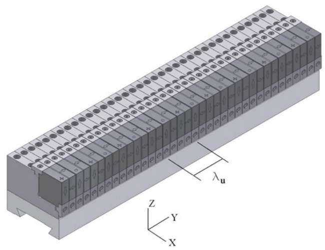

Figure 5: Undulator subcassette.

Once the induced voltage was measured, the conversion to magnetic field (B) is quite simple and can be determined directly by:

$$B_z(y) = \frac{1}{NSv}\int V(y')dy' + B_0 \qquad (4)$$

where V is the induced voltage, N is the number of turns, S is the mini coil area, v the scan speed and B_0 is the initial magnetic field .

PRELIMINARY RESULTS

Rotating Coil Results

Some preliminary tests of the mini coil inside the Helmoltz coil configuration were done and the results compared to Sentron hall probe measurements. The magnetic field generated by the Helmholtz coil was changed from -0.0014 teslas to 0.0012 teslas in steps of 4.3×10^{-5} teslas in the first test and the results are shown in Figure 6.

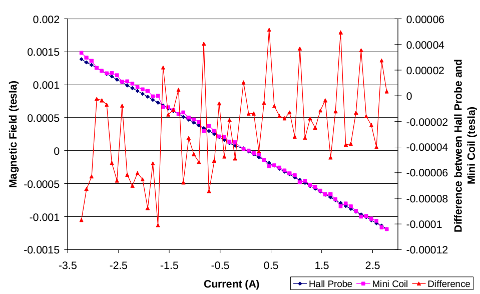

Figure 6: Rotating coil x Hall probe measurements inside of a Helmholtz coil configuration. The difference between Hall probe and the mini coil fields are expressed in the right side axis.

Figure 7 shows the results of the repeatability test of the mini coil where the Helmholtz coil was excited with an average current of 2.9987 ± 0.0009 Amps and about 60 measurements were done.

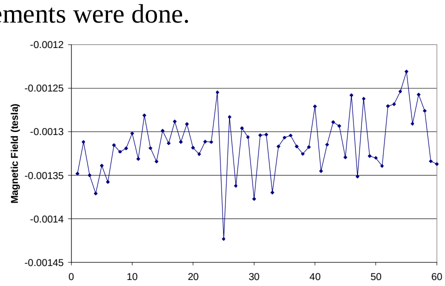

Figure 7: Repeatability test of the mini coil.

The standard deviation of the repeatability as well as the difference between hall probe and mini coil is around 0.35 gauss.

Scan Coil Results

Figure 8 presents a magnetic field profile of an undulator subcassette measured with both Hall probe and mini coil. Since de position of the Hall probe is not exactly the same of the mini coil, the signal of the mini coil was multiplied by a constant to make the average amplitudes closer. The right side axis in the graph is showing the difference between the techniques, given an idea of the agreement in the preliminary tests.

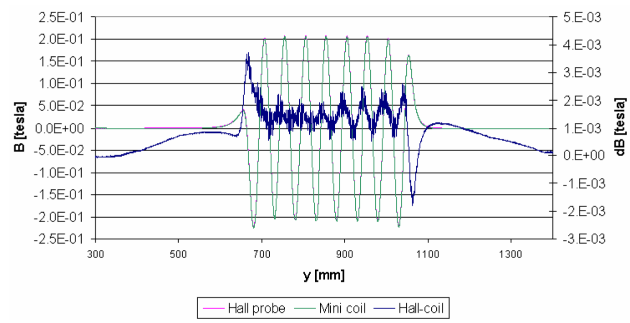

Figure 8: Graph showing the magnetic field of an undulator subcassette measured with both techniques: Hall probe and mini coil. The difference between the techniques is in the right side axis.

CONCLUSIONS

Some preliminary tests were done to verify the possibility of measuring local magnetic fields with the mini coil in two different configurations: as a rotating coil and a scan coil. Some improvements must be done to assure position repeatability and alignment in both methods and to correct the offset drift of the voltmeter. Also, an effort to improve the agreement with hall probes and the field precision must be done.

REFERENCES

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[2] Hwang, C.S.; Lin, Fu Yuan; Fan, Tai-Ching. Integral magnetic field measurement using an automatic fast long-loop-flip coil system. IEEE Trans. Instrum. Meas. v.52, p.865-870, 2003.

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