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PAPER

Well balanced pick-up assembly for double pulsed magnetic field apparatus

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Abstract

The generation of high magnetic pulsed fields involves several technological challenges. State-of-the-art field peak intensities can be achieved by means of double-coil systems and, as for other configurations, a special pick-up system is required to clean the signal from spurious components and artifacts. However, the design of a well-balanced pick-up for double-coil systems is not a trivial task because of the different mutual inductance of the two field coils. In general the pick-up can be optimized for one coil only, but not for both. Here we present a new pick-up concept specifically aimed at solving this problem, based on an active compensation bridge and a special compensating coil located outside field-generating coils. Besides yielding a good balance of the signal over all pulse duration, a further advantage is an additional increase in the signal-to-noise ratio.

1. Introduction

It is well known that the only method to generate very high magnetic fields is to drive energy into a field-generating coil wound with special wire (this coil works in all respect as a magnet and will therefore be called in the following the magnet) [1–7]. A typical example is the discharge of energy previously stored in a capacitor bank: where the duration of the obtained magnetic pulse depends only on the bank capacity and inductance of the magnet, while the maximum generated fields are also function of the total discharged energy. This is true for the use of spark gap and thyristor switches. But if IGBT (Insulated-Gate Bipolar Transistor) based switch is used then magnetic pulse duration can be controlled as well. The upper limits to the achievable fields are given by the performance of the magnet coil, whose conductor is subjected to the Lorentz force and ohmic heating. These factors can easily cause destruction of the magnet, either for the enormous electromagnetic pressure and for over-heating leading to short-circuit between adjacent magnet loops, thus one builds coils with conductive materials that combine optimal strength and conductivity. The strength can be brought about by inherent strength of the conductor itself and by external and distributed reinforcement. Different technologies are used to reinforce the magnet, such as mechanically very strong jackets reinforced with glass or carbon fiber, impregnated with epoxy resin and placed around the magnet. A common practice is cooling the magnet into liquid nitrogen to increase the stiffness and strength of the wire and reinforcement jacket, to decrease the winding electrical resistance and dissipate the heat generated during the pulse. Achieving very high magnetic fields is possible in the case of single-shot destructive magnet, for example the flux-compression method can reach fields in the MOe (Mega Oested) range [8–10]. In contrast to flux-compression, the single-turn coil technique produces MOe fields by the direct discharge of a fast capacitor bank into a small single-turn coil [8]. A more recently introduced technique involves the use of double coil magnets [6, 11–16]. In these systems, two different magnetic pulses are generated: a slower pulse brings the system to the beginning of the field region of interest, and a faster pulse gives the last push to reach the field peak (see figure 5, upper panel). Of course, to obtain such a peak shape each magnet coil must be connected to a different capacitor bank in such a way to have two sections with different time constants. Regardless of how the field pulse is generated, the signal coming from the measured sample is detected by a pick-up coil that has to be “compensate”, meaning that it needs some additional “compensation” coil whose function is to cancel out the component of the detected signal coming

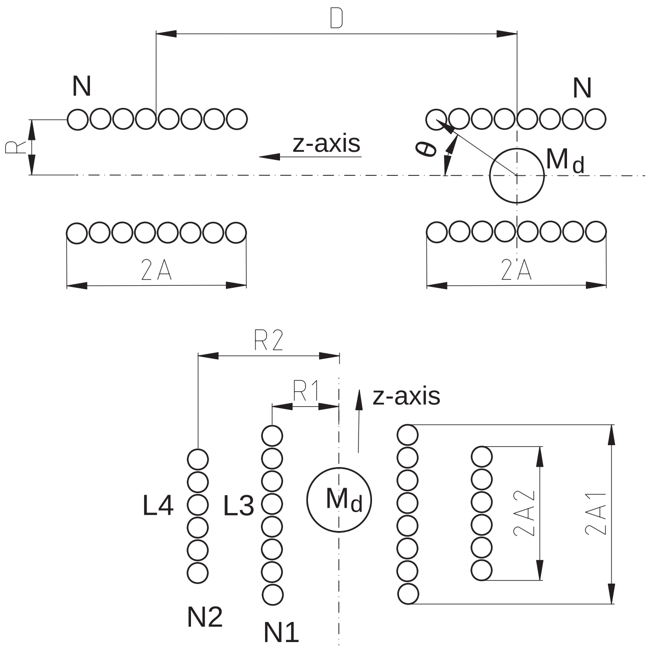

Figure 1. Sketch for calculation of the induced signal of a sample dipole moment (M_d) in the Helmholtz-like configuration (upper) and in the coaxial configuration (lower).

from the magnetic pulse itself, electronic offsets and other possible artifacts. Much effort has been made in this regard. A typical simple pick-up assembly consists of two coils wound with opposite chirality (clockwise and counterclockwise) in a Helmholtz-like configuration, plus a small compensating coil previously partitioned in such a way as to give a zero signal for blank measurements. The sample to be measured was positioned in one of the two coils, and the detected signal was proportional to the derivative of the magnetization with respect to time. A different configuration was given by Trojanowski where all the pick-up coils were coaxially wound , he presented a method for determining the effective coefficient of coupling between the coil set and cylindrical samples, which is useful for the calculation of the sample induced signal [17]. In addition Eckert concluded that the concentric arrangement is better from the point of view of the sample displacement with respect to the magnet center [18]. Interesting studies have been carried out on the effect of stray capacitance on the sensing and compensation coils [19]. In the case of a single turn for the generation of a megagauss field, different configurations of pick-up were tested with the conclusion that the concentric arrangement is the best solution for what may concern the stability against possible small displacements of the pick-up around the magnet center [20]. Similar conclusions have been drown by Skourski *et al* [21]. In general compensation operation and calibration with a reference sample must be performed at every working temperature of the pick-up. The amount of knowledge built up in the literature about this subject is significant; nonetheless, all the known solutions are not suitable for the case of double magnet systems. In fact the aforementioned partitioning of the compensating coil depends on the coupling with the magnet coil. In double-magnet systems, the two magnet coils have very different characteristic frequencies and mutual inductances, so that the compensating coil can be properly balanced with one of the two magnet coils but not with both. In the following we present a well-balanced pick-up suitable for use in double-pulsed field systems, whose main feature is an active compensation pick-up joined to a very large compensating coil located outside the magnet. To our knowledge, no similar assembly has yet been previously shown in the literature.

2. Instrumental setup

It is interesting to compare the signal given by the magnetic sample in the case of the Helmholtz-like coil configuration with that in the coaxial configuration. Figure 1 shows a sketch of the two systems. Let us assume that the shape of sample (M_d) is spherical and that it is magnetized homogeneously with the magnetization vector along the coil axis, that is parallel to the direction of the magnetic field. In the following we can consider the sample as a magnetic dipole, so its induction at a point with coordinates $(r, \cos\theta)$ with respect to its center is:

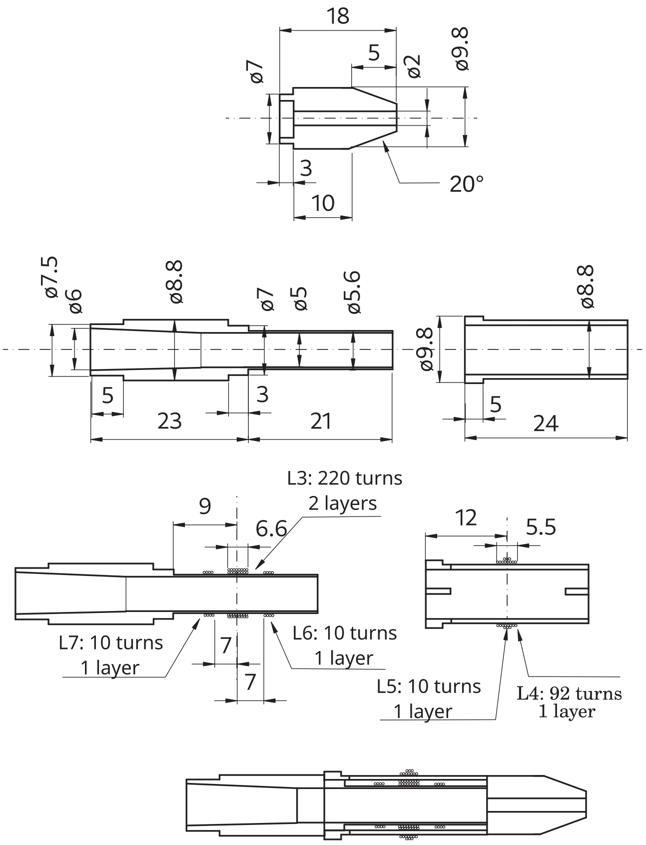

Figure 2. Upper: drawing of the pick-up support made by insulating composite material (Carp Brand Tufnol), all dimensions in mm. Center: coil wingdings all made by Teflon enameled CuBe wire with $\phi = 0.06mm$. Lower: assembled pick-up.

$$B_z = \frac{M_d(3\cos^2\theta - 1)}{r^3} \tag{1}$$

where θ is the angle between the z and r directions and M_d is the magnetic dipole moment ($emu = Gauss\ cm^3$) of the sample oriented along the z axis. The flux through a single turn with radius R at distance z from the dipole is the integral of equation (1) on the turn area:

$$\phi = \frac{2\pi M_d}{R}\sin^3\theta \tag{2}$$

where $\sin\theta = R/(R^2 + z^2)^{1/2}$.

The flux through the coaxial pick-up is obtained by integrating equation (2) on the entire length of coils $L3$ and $L4$ which are wound with opposite chiralities:

$$\phi_t = 2\pi M_d\left(\frac{N_1}{\sqrt{R_1^2 + A_1^2}} - \frac{N_2}{\sqrt{R_2^2 + A_2^2}}\right) \tag{3}$$

where $N1$, $N2$ and $R1$, $R2$ are the number of turns and the radii of the two coils and must meet the condition $R_1^2 N_1 = R_2^2 N_2$, in order to ensure a null signal in the absence of the sample. The flux through the coaxial pick-up can be calculated in the same manner. As an example introducing reasonable values as below $R_1 = R = 2.8$ (mm), R_2=4.4 (mm), $2A_1 = 2A = 6.6$ (mm), $2A_2 = 5.5$ (mm), $Z = 12$ (mm) , $N_1 = N = 220$ and $N_2 = 92$, we obtain for the Helmholtz system $\phi_H = 3.19 \cdot 10^3 M_d$ while for the coaxial system $\phi_t = 2.08 \cdot 10^3 M_d$. The units for ϕ are $Gauss/cm$ and emu ($emu = Gauss/cm^3$) for M_d. We chose the coaxial configuration for our pickup because it is less sensitive to mechanical vibrations, although it is less sensitive to the sample signal with respect to the Helmholtz-like coil. All physical parameters, which are exploded for clarity, are shown in figure 2. As explained below, coils $L5$ and $L8$ where added to the two main pick-up coils $L3$ and $L4$ to improve compensation. In particular, note that the widest coil $L8$ is wound around the whole assembly for the reason explained below and does not appear in figure 2 because of its large diameter, details are given in figure 3.

The supports we made of composite material, fine fabric impregnated with phenolic resin (Carp Brand Tufnol), and each coil was wound by copper beryllium alloy wire enameled by Teflon with a total diameter of 0.06 mm. Beryllium copper (2% Beryllium) is much more resistant than pure copper to thermal stress, so the

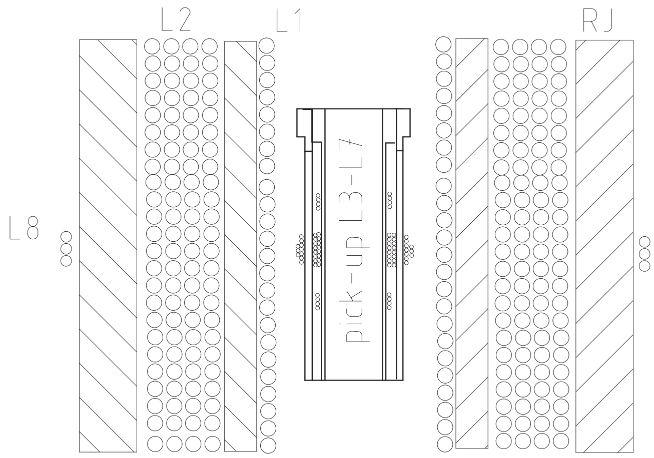

Figure 3. Experimental assembly, $L1$ and $L2$: doubled pulsed magnet for strong field generation, RJ: reinforcement jacket made by impregnated S2 glass fibers, $L3$ to $L8$: pick-up system, the outer coil L8 detects the slow part of the signal (see text).

Table 1. Physical characteristics of all inductances, dimensions are *mm.* $L1$ and $L2$ are the coaxial coils of the magnet that generate the double pulsed field.

Coil name	Inner diameter	Outer diameter	Coil length	Turn number	Inductance microH
L1	45	113.2	160	119	345
L2	27.4	33.4	152	41.5	10
L3	5.6	5.84	6.6	220	163
L4	8.8	8.92	5.5	92	65.8
L5	8.92	9.04	0.6	10	1.72
L6	5.6	5.72	0.6	10	0.985
L7	5.6	5.72	0.6	10	0.985
L8	200	201	1.5	3	3.9

pick up will have a long life. Special grooves (not shown in Fig, 2) were made longitudinally on the supports to fix the terminal wires of each coil. All parts were glued together using an epoxy resin.

First, $L4$ is wound with 96 turns, a number is slightly in excess with respect to the calculated value (see TABLE I), then $L3$ is temporarily anti phase connected to $L4$. The pick-up was introduced into an exciting coil driven by a current with the same frequency as the working coil. Using a lock-in amplifier, we remove the extra turns to obtain a signal as close to zero as possible, after which the $L5$ coil was wound on top of $L2$. To avoid a high voltage on the connecting wires $L3$ and $L4$ are finally anti phase locally connected. The combination of $L4$ and $L5$ is very useful for centering the pick-up along the magnet axis.

The pick-up assembly is glued to a long tube made of the same material, and the terminal wires of the coils are locally soldered to a copper wire (diameter $0.1mm$) to reduce the total resistance of the connections. The wires are twisted together to avoid spurious signals and to reduce the stray capacitance. The physical characteristics of all coils are summarized in tables 1 and 2, where we calculated only the main mutual inductances and coupling factors, since pick-up coil currents are negligible and some mutual couplings are minimal. We used the values of table 1 to simulate, using Spice software, the entire system to verify the coherence of the given assumptions.

In figure 4 the circuit wiring of the pick-up coils is shown together with the compensation active bridge. The main pick-up coils $L3$ and $L4$ are connected in series and the electric signal measured at the ends of the $L1 - L3$ unit is given by Faradays law. $L3$ and $L4$ are counterwise wounds; therefore, the contribution to the signal coming from the magnetic pulsed field, which is uniform over the pick-up area, is zero. However, according to equation (1) the magnetic field of a sample located inside the pick-up is not uniform, and the slight difference in the cross sections of $L3$ and $L4$ is sufficient to leave a sizeable net signal coming from the time variation of the sample magnetization. In this way a rough compensation is obtained, but there is still a need to compensate for the residual contribution from the magnetic field owing to the cross-section difference. This task was accomplished as follows: Part of the signal of $L5$ is shifted in time by C and $R3$ and summed through the partition resistor $R1$. The obtained signal was amplified using the operational amplifier $Is1$. Part of the signal given by $L8$, which is also part of the pickup, is sent to the operational amplifier $Is2$ through partition resistor $R2$. The outer

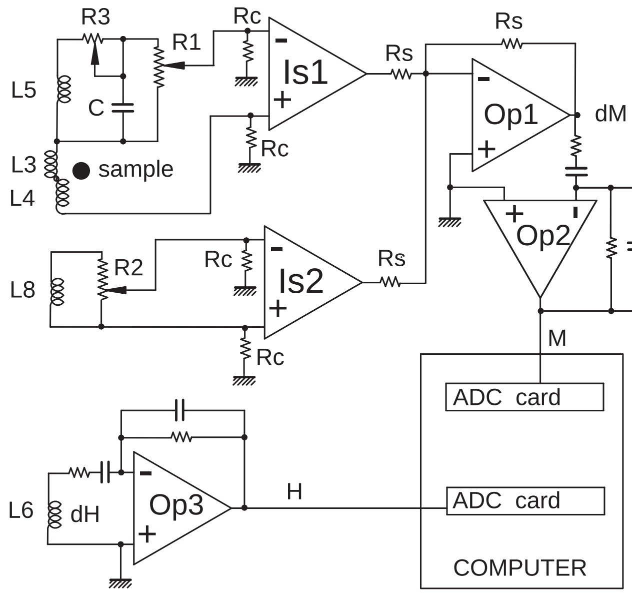

Figure 4. Active compensation bridge: the pick-up system is given by coils *L*3 to *L*8, *Is*1 and *Is*2 are wide band instrumentation amplifiers and *Op*1 is a wide band operational summing amplifier. Its output, dM/dt if a magnetic sample is present, is integrated by *Op*2 giving the magnetization $M(t)$, L6 gives the field derivative signal dH/dt that integrated by *Op*3 yields $H(t)$, both $M(t)$ and $H(t)$ are sent to ADC cards inside a computer. From $M(t)$ and $H(t)$ one can obtain the magnetization curve $M(H)$.

Table 2. Coupling coefficients for each coil pair.

Coil types	M microH	K	Coils types	M microH	K
L1-L2	23.34	0.397	L2-L3	1.902	0.047
L1-L3	4.611	0.0194	L2-L4	1.908	0.0744
L1-L4	4.626	0.031	L2-L5	0.2131	0.054
L1-L5	0.517	0.0212	L2-L6	0.0865	0.0276
L1-L6	0.205	0.0111	L2-L7	0.0865	0.0276
L1-L7	0.205	0.0111	L2-L8	0.45	0.072
L1-L8	9.35	0.255			

pins of *Is*1 and *Is*2 are summed by operational amplifier *Op*1 giving the final output, corresponding to dM/dt if a magnetic sample is placed inside the pick-up. This well compensated output is then integrated by *Op*2, obtaining the magnetization $M(t)$. The derivative of the magnetic field with respect to time dH/dt is given by *L*6 and is integrated by *Op*3 giving the magnetic field $H(t)$. Both $M(t)$ and $H(t)$ are sent to two analog-to-digital converter card ADC from which one can obtain the magnetization curve $M(H)$. Connecting the high input impedance instrumentation amplifiers *Is*1 and *Is*2 directly to the pick-up coils, before the summing amplifier *Op*1 (active configuration) , has the advantage of amplifying the pick-up signal without lowering the signal to noise ratio.

3. Results and discussion

After explaining the working principle of the pick-up, we now present the result of a real double-pulse experiment. The experiment will be carried out at low field and room temperature conditions to highlight the benefits of this method, eliminating uncontrolled vibrations that can appear at very high field and low temperature and cannot be eliminated even using sophisticated pickups. The two magnet coils *L*1 and *L*2 receive the discharged energy from two separate capacitor banks with capacitance $C1 = 0.003F$ and $C2 = 0.22F$ respectively. The faster coil *L*1 is a single layer, whereas the slower coil *L*2 is a multilayer. Both *L*1 and *L*2 are protected against radial forces by a reinforcement jacket made of impregnated S2 glass fiber. A typical pick-up signal from an experiment without sample, before full compensation, is shown in figure 5.

The measured signal is the induced voltage resulting from the Faradays law and depends on the time derivatives of the magnetic flux and therefore on the derivatives $dI(L1, L2)/dt$ of the current through the magnet coils, hence on the fundamental frequency of the two pulses, and on the corresponding couplings $M((L1, L2), (L3, L4))$ of the

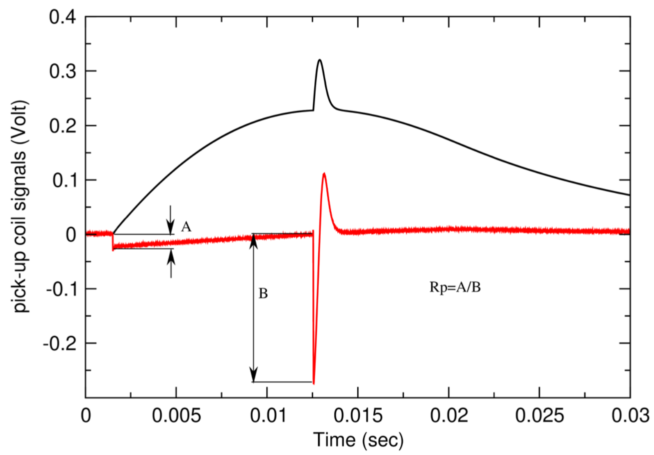

Figure 5. Example of unbalanced pick-up coil signal $V_{L3,L4}$ (red) and the corresponding magnetic field (black) obtained by integrating the signal of the coil$L6$, capacitor banks $C1$ and $C2$ are charged with 200 and 400 Volts respectively.

two magnet coils with the pick-up coils. In particular the voltage at the terminals of sections $L3 - L4$ is:

$$V_{L3,L4} = -(M_{L1,L3} - M_{L1,L4})\frac{dI_{L1}}{dt} - (M_{L2,L3} - M_{L2,L4})\frac{dI_{L2}}{dt} \quad (4)$$

Note that the experimentally measured rising time of $L1$ and $L2$ are 0.35 ms and 11.015 ms respectively, so that the corresponding frequencies are orders of magnitude different. Moreover, all the induced signals depend strongly on the combination of various mutual coefficients, and as shown in figure 5, they have different values of quantities A and B, a high value of the ratio $R_p = B/A$, which in the end is the parameter that we need to minimize. Trying to compensate in a naive way by adding a signal from an extra coil, such as for instance $L5$ or $L7$, we can compensate for either the slow or the fast part of the signal but not both. It is necessary to have a compensating signal where it is possible to vary the slow and fast parts of the signal in such a way as to vary the ratio R_p. In principle, it is conceivable to separate the slow part from the fast part by proper filters, but because the two signals contain both high and low frequencies, this solution is impracticable. We present an alternative solution that relies a further coil $L8$ which is wound on the exterior of the reinforcement of the entire magnet assembly. The different couplings of $L8$ with $L1$ and with $L2$ allow to lower the R_p ratio, yielding an almost independent compensation signal for the slow part of the pulse. The $L8$ coil also has a worth mentioning side benefit, namely that looking at its signal after each capacitor discharge it is possible to detect extra anomalous noise anticipating magnet failure. Although even the internal pick up can reveal the same anomalous noise, the external coil is much more sensitive to possible breakages, which are more likely in the external coil which has a higher energy density.

It is interesting to analyze point C highlighted in figure 6, defined as the intersection point with the zero volt axis of the signals from each coil of the system. The position of the C point is a lightly different for the various coils, with the difference ranging from -4 to $+4\mu$ sec, and it is easy to overlap the C point of $L5$ with that of $L3 - L4$ by the small time constant RC filter labeled $R3 \cdot C$ in figure 4. This small effect originates from several causes: the pulse shape is not perfectly sinusoidal because of variations in the damping factors which in turn originate from the increment in temperature during the capacitor discharges, the complexity of the various tangled mutual couplings, and small differences in stray capacitances. Alignment of various C points is essential for perfect balancing. The signals generated for some coils are shown in figure 6: where the signal of $V(L3) + V(L4)$, which is not yet well compensated, is magnified five time for clarity, and at this stage the compensation ratio $(V(L3) + V(L4))/V(L4)$ is 1: 112.

The compensation procedure is as follows (refer to figure 6 and 7): First we tune $R1$ to obtain a signal as small as possible (black signal in figure 7, then we tune $R3$ to have a good coincidence of the C points of $L5$ and $L3 - L4$, see red right signal, and finally we tune $R2$ to compensate for the low-frequency signal by $L8$, see the red left signal. The second and third steps are then repeated to improve the result. The typical ratio of the balanced voltage Vout versus the voltage of $L4$ is approximately 1:400000.

It is interesting to calculate the order of magnitude of the pick-up signal obtained by a magnetic sample by numerical simulations and compare it with the corresponding experimental results. As an example let us consider a sphere of an isotropic magnet of Barium ferrite ($BaFe_{12}O_{19}$) with diameter $\phi = 3.3mm$. The

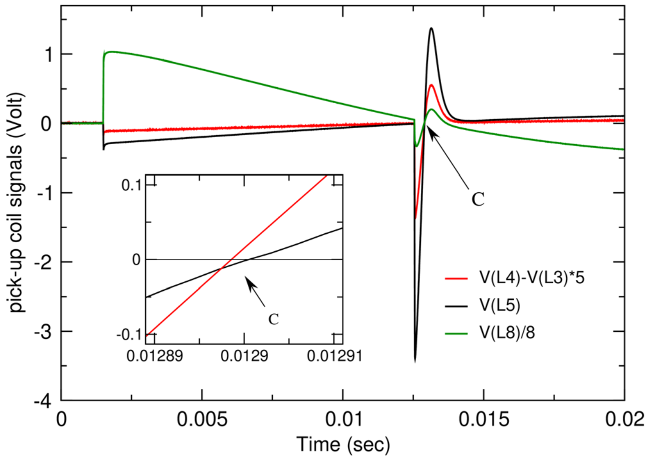

Figure 6. Voltage generated by some pick-up coils, the $V(L4) - V(L3)$ and $V(L8)$ signals are zoomed by 5 and 0.125 respectively. Inset amplified view of the crossing signals with the zero volt axis.

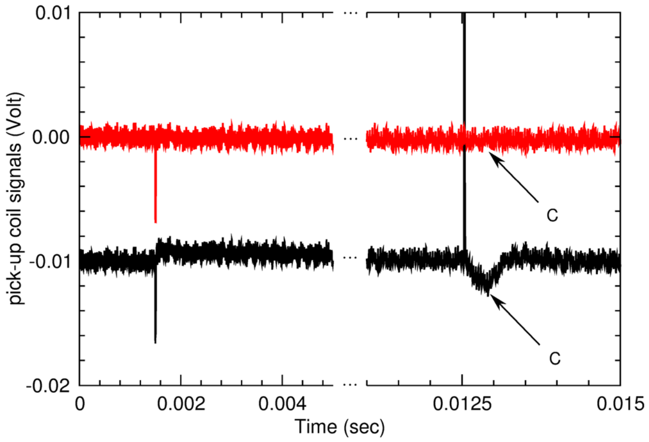

Figure 7. Comparison of experimental results of a blank (i.e. without sample) measurement. Black curve: first rough balancing obtained tuning R1 only; Red curve: final well compensation obtained tuning also *R*2 and *R*3. The time axis is split into the two critical zones corresponding to the start of the two magnetic pulses. R2 is used for tuning on the time zone on the left, *R*3 is used for tuning on the time zone on the right.

calculated induced voltage is:

$$V_1 = -\frac{1}{c}\frac{d}{dt}\phi_t = -\frac{2.08 \cdot 10^3}{c}\frac{dM_d}{dt} = -\frac{2.08 \cdot 10^3}{c}\frac{dM}{dH}\frac{dH}{dt}v \quad (5)$$

where $M_d = M \cdot v$ is the magnetic dipole moment, M is the magnetization of $BaFe_{12}O_{19}$ and v is the volume of the sample.

The initial susceptibility in the Stoner Wolfhart model is $dM/dH = 2/3 \cdot Ms/H_A = 1.49 \cdot 10^{-2}$ where $Ms = 380 emu/cm^3$ is the saturation magnetization and $H_A = 17 \cdot 10^3 Oe$ denotes the anisotropy field. If only the magnet coil $L1$ is energized charging the corresponding capacitor bank at 400 volt, we have a field slope $dH/dt = 8.98 \cdot 10^7 Oe/sec$ with pick-up signal $V1 = 1.73 \cdot 10^{-3}$ statV or 0.52Volt, conversely if only coil $L2$ is energized with the same voltage we have $dH/dt = 1.0 \cdot 10^7 Oe/$sec and $V2 = 1.93 \cdot 10^{-4}$ statV or 0.058Volt. In both cases the instrumentation amplifier gain of $Is1$ and $Is2$ were equal to 1. The experimental measurements yielded corresponding signals $V1 = 0.40$ and $V2 = 0.045$ V respectively, in good agreement with the calculated values. The obtained $V1$ and $V2$ signals formally correspond to the values B and A in figure 5 (formally means that the true values A and B are now different because of compensation).

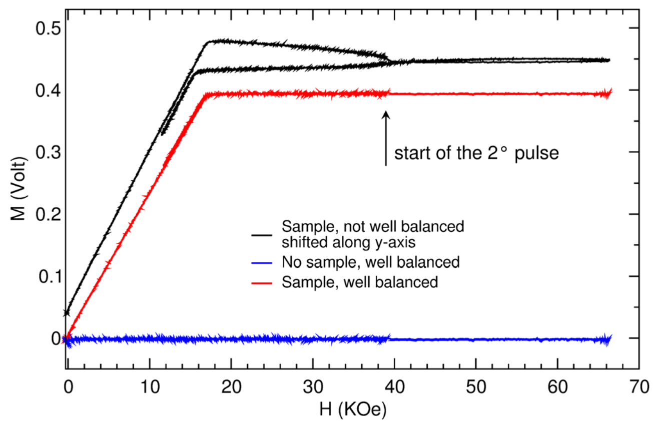

Figure 8. Experimental magnetization result of $BaFe_{12}O_{19}$ single crystal, for the case of roughly and well balanced pick-up.

To verify the linearity of the compensation procedure a further experiment was performed on a $BaFe_{12}O_{19}$ single crystal in which the magnetization values were perfectly linear with respect to the applied magnetic fields. The magnetization results obtained by integrating the pick-up signal are shown in figure 8. The black curve is the result of the simple pick-up in the case in which one has chosen to compensate for the fast part of the signal, the red curve is obtained by the well-balanced pick-up described above, and the blue curve corresponds to the blank measurement, that is the signal recorded with the empty sample chamber. It is clear from these results that a simple pickup is not suitable for double pulsed magnetic field applications. What about high magnetic field experiments? From our experience, balancing done at a relative low magnetic field works very well at higher fields, it is usual practice to balance at a low field, in fact many pulses are needed to achieve perfect balancing, avoiding unnecessarily stressing the magnet at high fields.

4. Conclusions

In conclusion we presented a pick-up coil specially designed for double magnetic pulse systems, which are currently used for the generation of very high magnetic fields in the study of the properties of magnetic materials. The working principle relies on an active compensating bridge and special compensating coil added outside the entire double-magnet assembly. The function of the latter coil is to add a low-frequency signal that is critical for obtaining a well-balanced compensation along all magnetic pulse duration. A further benefit is an improved signal-to-noise ratio (SNR). We tested this pick-up on two $BaFe_{12}O_{19}$ samples, a polycrystalline reference sample and a single crystal and obtained a good agreement with the expected results.

Data availability statement

No new data were created or analysed in this study.

Conflicts of interest

The authors have declared that no competing interests exist.

Data access statement

The data that support the findings of this study are available upon request from the authors.

Ethics statement

Not applicable.

Funding statement

Not applicable.

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