Digital BH-meter based on NI DAQ:

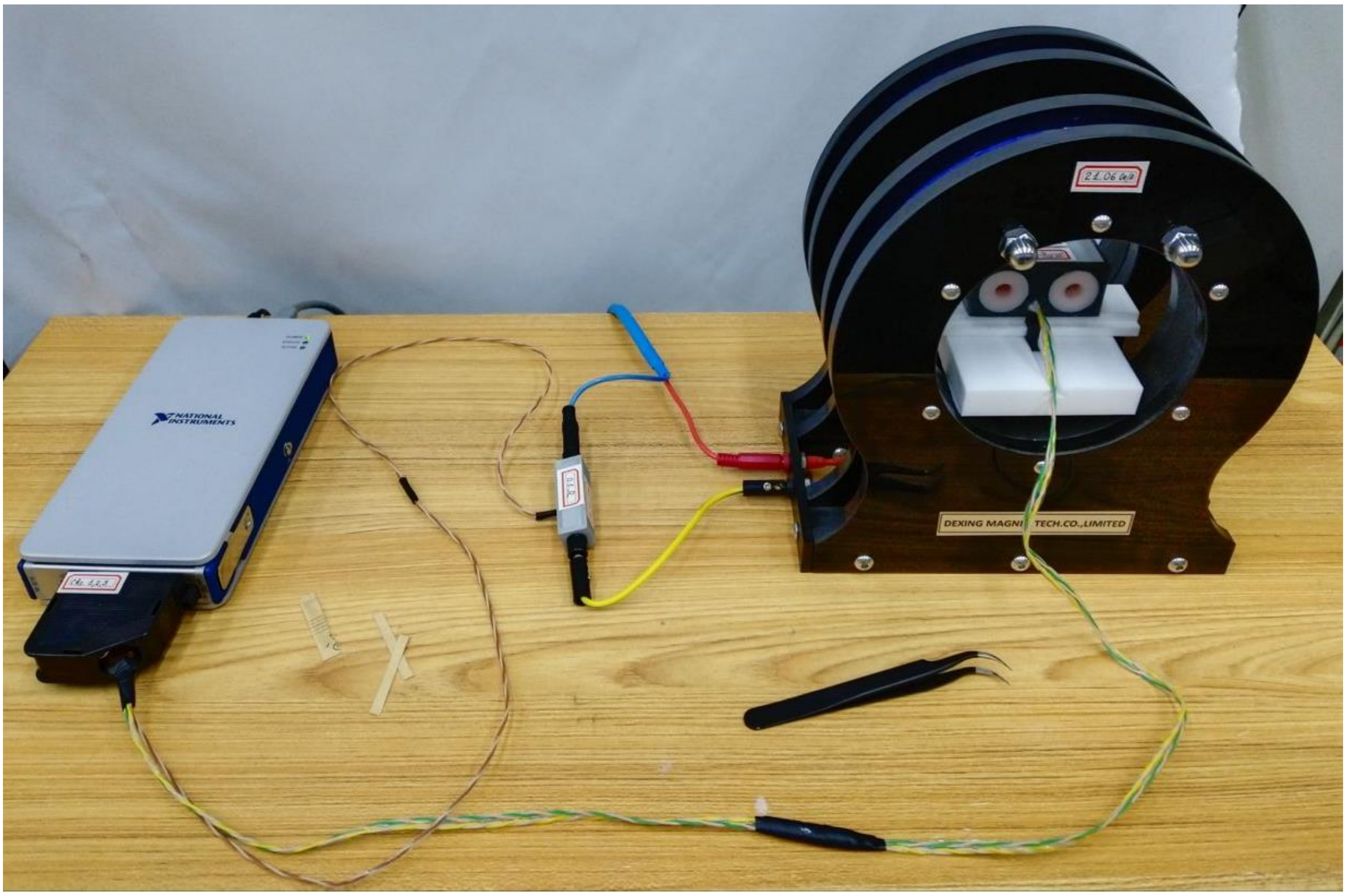
user manual and full design report

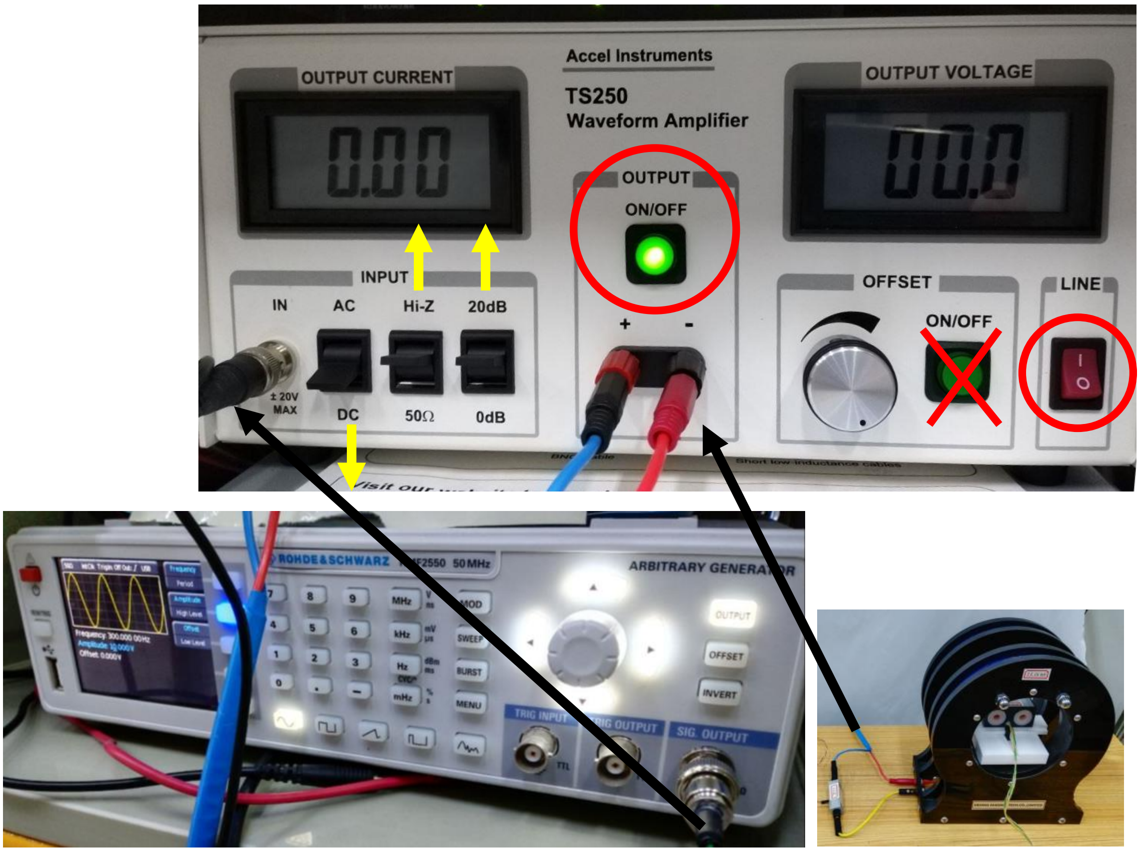
Contents

User manual

1) Measurement setup

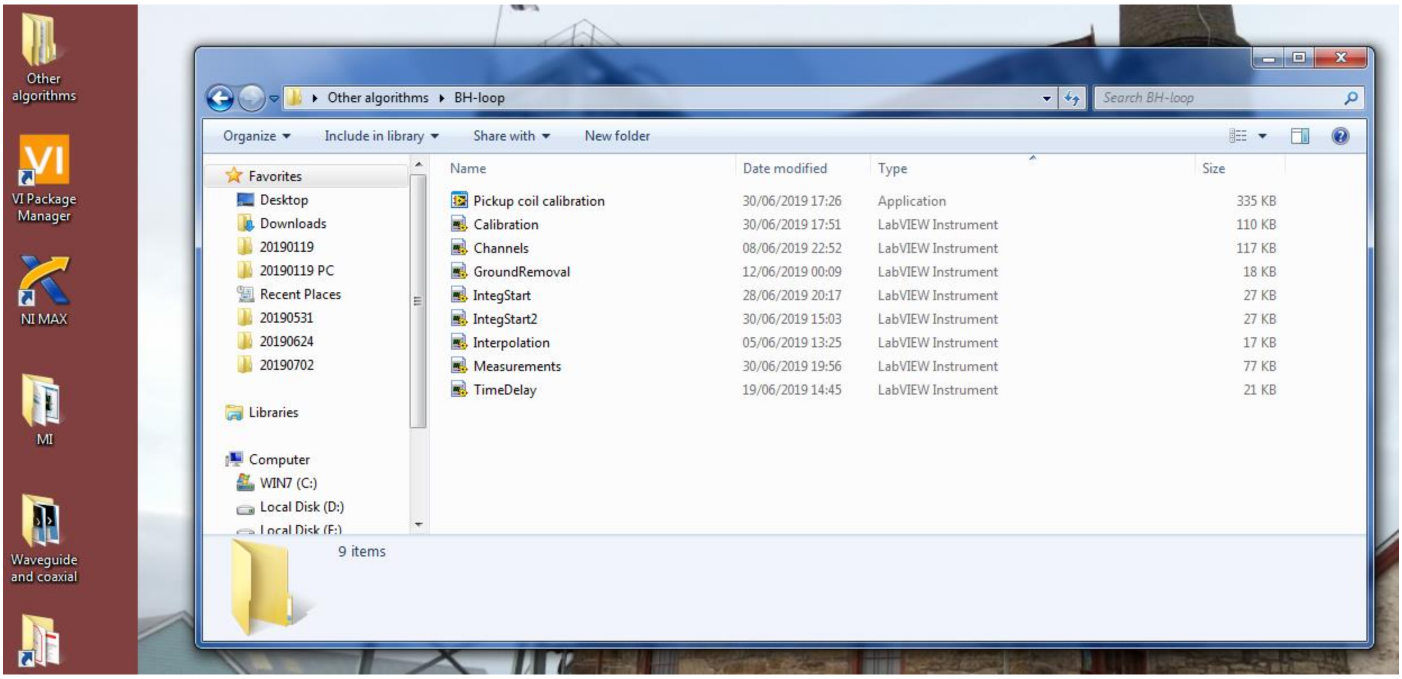
Install the BH-meter measurement setup as shown below. Place the pickup coils onto the in-plane adjustable platform inside the Helmholtz coil. Connect NI DAQ 9215 (National Instruments Analog to Digital Converter) to LAN. Switch on Rohde&Schwarz HMF 2550 function generator. Run NI MAX (Measurement & Automation Explorer) and check that NI DAQ and HMF are connected to PC. Connect the Helmholtz coil to TS250-2 waveform amplifier through the in-series current sensor (0.1 Ω resistor). Connect TS250-2 waveform amplifier to HMF. HMF and DAQ will be controlled by a LabVIEW program, interface of which is described below.



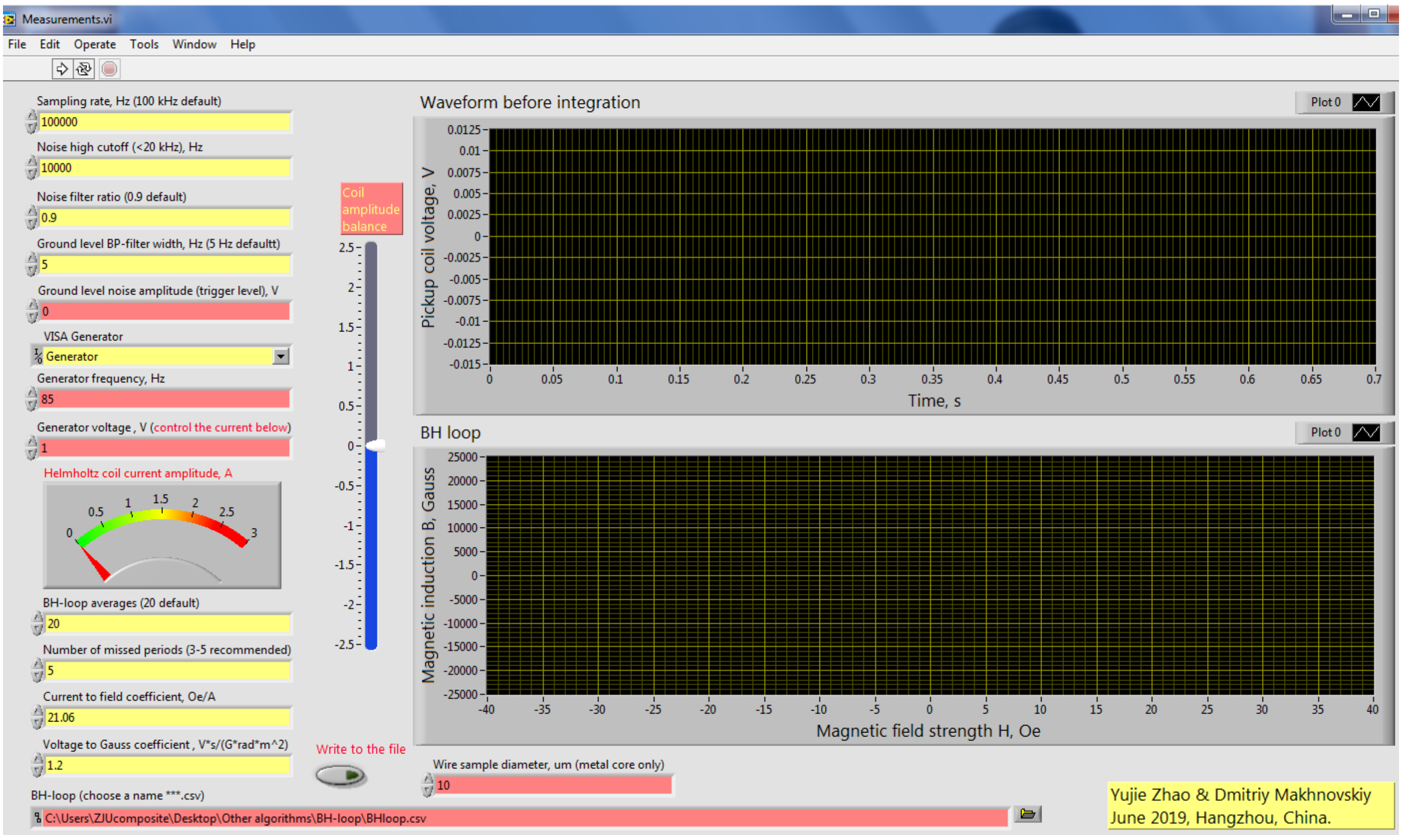


2) Program interface

Run **Measurements** LabVIEW VI (Virtual Instrument) in the folder shown below (on PC desktop). The other files in this folder are subroutines called by Measurements. And, **Pickup coil calibration.exe** is used for calibrating the pickup coils as described in the design report. Do not remove these files from the folder.



The user interface of Measurements is shown below.



During the coil balancing and adjusting other parameters, the program should be run in the continuous mode. To write down the final BH-loop to a *****.csv** file: (i) stop the program after continuous running, (ii) switch on the toggle Write to the file, and (iii) run the program again in the single mode. The program could be run several times before obtaining the best loop. *When closing the program, choose "do not save" changes.* The interface parameters marked in yellow are universal and rarely changed, while the parameters marked in pink may be modified for each test (but they also have some default values):

- **Sampling rate (100 kHz default)** – maximum sample acquisition rate for NI DAQ 9215. Do not change this parameter.
- **Noise cutoff (< 20 kHz), Hz** – high cutoff frequency of the low-pass filter applied to all three measurement channels (from two pickup coils and current sensor). We recommend 10 kHz, but for some samples one could try lower or higher frequencies depending on the rate of the magnetisation reversal. Look at "Waveform before integration" to estimate the filter influence on the signal. Choose the cutoff frequency to suppress high frequency noise but at the same time save the signal main features.
- **Noise filter ratio (0.9 default)** – low cutoff frequency of the low-pass filter calculated as 0.9 × high cutoff frequency.

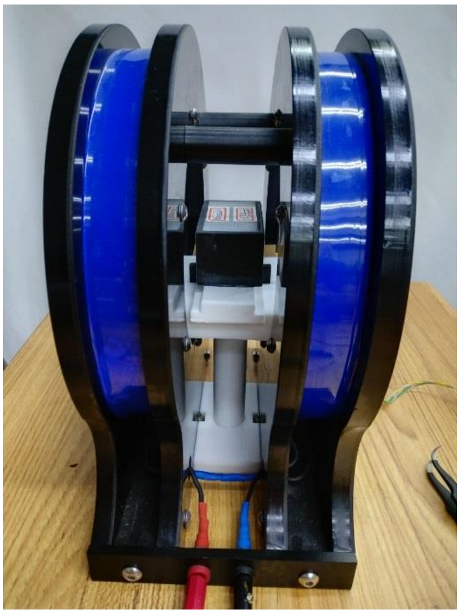
- **Ground level BP-filter width, Hz (5 Hz default)** – spectral width of the band-pass (BP) filter. The ground level, which is observed as low frequency noise, is selected by BP for its further subtraction from the main differential signal obtained from the pickup coils. BP filter is constructed as the low-pass and high-pass filters connected in series. The generator frequency f_g constitutes the low cutoff frequency for the low-pass filter and the high cutoff frequency for the high-pass filter. The high cutoff frequency for the low-pass filter is calculated as $(f_g + \text{width})$, and the low cutoff frequency for the high-pass filter as $(f_g - \text{width})$.
- **Ground level noise amplitude (trigger level), V** – amplitude of the ground level after the mechanical and electronic balancing of the pickup coils. Balancing of the pickup coil will significantly reduce the ripple of ground level but not eliminate it completely. Despite its small amplitude as compared with the useful pulses, the ground level ripple significantly distorts the saturation level in the BH-loop when performing the integration (openings at the saturation levels). On other hand, since this ripple does not contain any useful information, it can be easily cut off by introducing a proper amplitude trigger level – all amplitudes below this level will be grounded to zero. Remove the sample, balance the pickup coil (mechanically and electronically), and then estimate the ground level noise. Then, put the sample back, balance the pickup coils again, and submit the estimated trigger level. It can be slightly adjusted looking at the "BH loop" graph.
- **VISA Generator** – VISA source for HMF function generator.
- **Generator frequency, Hz** – frequency of the excitation sinusoid that feeds the Helmholtz coil through the waveform amplifier. For the usual excitation scheme, without the compensating capacitor, the frequency cannot exceed 200 Hz. Otherwise, the current through the Helmholtz coil will not be strong enough to saturate the sample during the magnetisation reversal. To measure BH-loops at higher frequencies, the resonance excitation scheme must be used, which is discussed in the main report below. But the program interface will remain the same.
- **Generator voltage, V (control the current below)** – amplitude of the sinusoid supplied by the function generator. The maximum possible voltage, which can be applied to the waveform amplifier, will depend on the excitation frequency. Since the waveform amplifier will be operated with the gain 10 (20 dB/0 dB toggle is in the position "up" on the front panel; see the photograph above), the supplied sinusoid will have only several volts amplitude. When choosing the generator voltage, the current amplitude through the Helmholtz coil must be carefully controlled to avoid overheating the amplifier. Look at the pointer indicator "Helmholtz coil current amplitude, A" to control the current – it must not exceed 3 A. Actually, it is suggested keeping it below 2.5 A. The waveform amplifier has a current protection, so if overheated it will automatically disconnect the OUTPUT ON/OFF button – it will

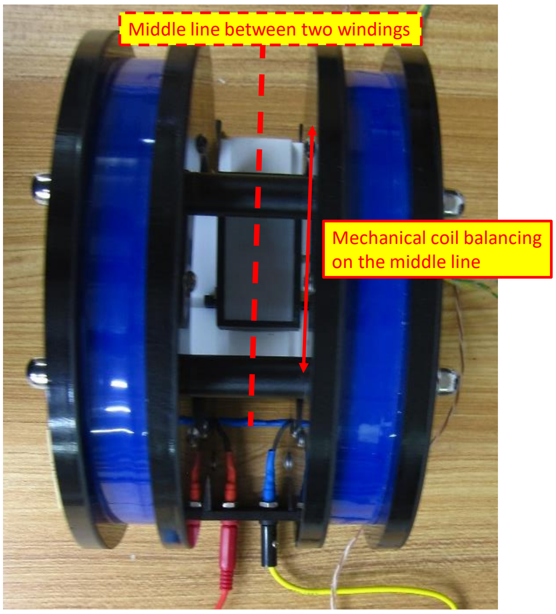
become flashing. In this case, immediately stop the program, reduce the voltage, run the program again, and then push the OUTPUT button.

- **BH**-loop averages (20 default) – number of the magnetisation reversals used to draw an averaged BH-loop. Each branch of a BH-loop is calculated the chosen number of times (20 default) and then averaged.
- **Number of missed periods (3-5 recommended)** – several first magnetisation reversal will be missed and not used for the calculations. This should be done because the low-pass and high-pass filters used in the program (see above) have transient times during which strong distortions can be observed.
- **Current to field coefficient, Oe/A** – coefficient obtained from the calibration of the Helmholtz coil that relates the current through the coil with the magnetic field induced by it.
- **Voltage to Gauss coefficient, V×s/(G×rad×m^2**) – coefficient obtained from the calibration of the pickup coils that relates the voltage measured across a pickup coil with the value of variable magnetic induction through it. The latter will be confined within the sample cross-section. The calibration procedure for the pickup coils is described in the main text of this report.
- **Wire sample diameter, um (metal core only)** – it is used for calculating the sample cross-section which is required to obtain the absolute value of the magnetic induction in the sample. When measuring several identical wire samples together, to obtain the value of magnetic induction in each individual wire, use the effective radius $r_{eff} = r\sqrt{N}$, where r and N are the radius of each wire (metal core) and the number of wires in the bunch respectively. Also, one may be interested in calculating the effective magnetic induction through the bunch of wires. In this case, use the total bunch radius. If the bunch has a cross section different from circular, use the effective bunch radius calculated as $r_{eff} = \sqrt{S/\pi}$, where S is the bunch cross section area.
- **BH**-loop (choose a name ***.csv) – choose a folder and a name of the csv file where the final BH-loop will be saved.
- **Coil amplitude balance** – this slide regulator is used for electronic balancing of the pickup coils in addition to the mechanical balancing described below.

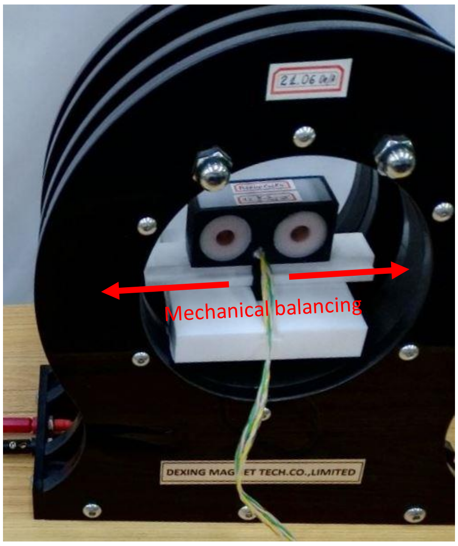
3) Balancing the pickup coils and measuring BH-loops

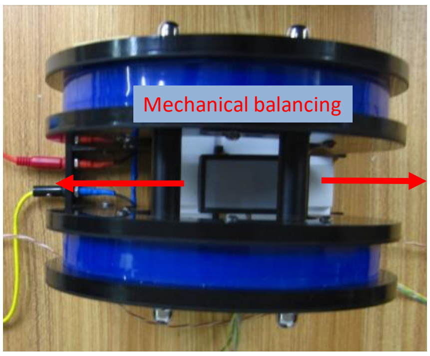
Before measuring BH-loops, the pickup coils must be balanced. Remove the sample from the pickup coil. Run the program in the continuous mode. Shift the movable platform with the pickup coils to the middle position between two windings of the Helmholtz coil as shown below.





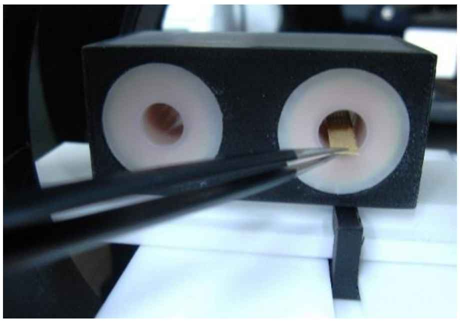
Run the program in the continuous mode. Put the slide regulator to zero. Then, looking at the graph "Waveform before integration", start slowly moving the platform together with the pickup coils to the left or right, as shown below, to obtain the minimum possible ground level amplitude (mechanical balancing). In some cases, a better balancing can be achieved by introducing a slight disbalance and then minimising the ground level using the slide regulator (electronic balancing). After the balancing, estimate the ripple amplitude of the ground level (low frequency noise). This ripple amplitude can be used for the trigger level: all signal amplitudes (±) below this level will be grounded to zero.





In the middle position between the windings of Helmholtz coil

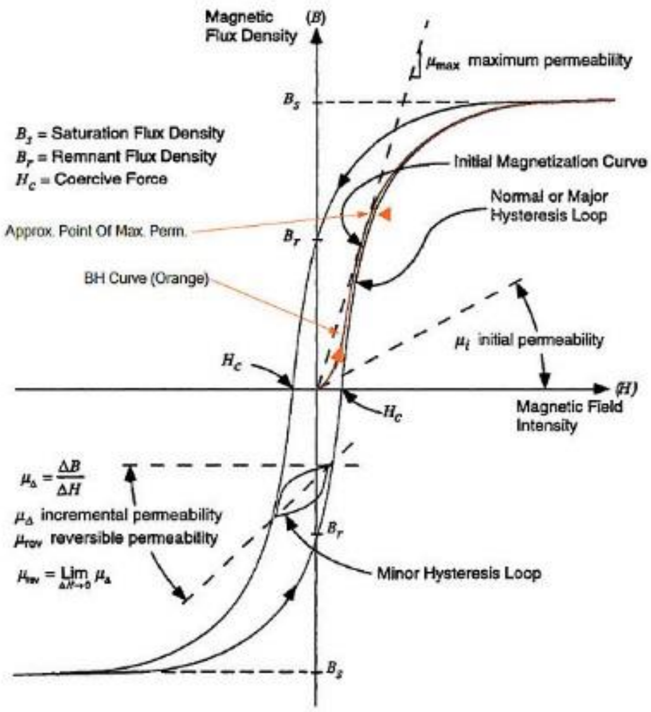
Run the program in the continuous mode. Accurately put the sample into one of the pickup coils using tweezers, as shown below. Avoid touching the pickup coils. BH-loops measured from the sample placed into the left or right coil will be mirrored with respect to the vertical B-axis. Run the program in continuous mode and, looking at the graph "BH loop", additionally adjust the coil balancing using the slide regulator. Try to minimise possible artefacts on the BH-loop and obtain proper saturation levels for the induction B.



If satisfied with the shape of BH-loop, stop continuous running, switch on the toggle Write to the file, and run the program again in the single mode. During each single run, BH-loop will be written into the specified file. Try several times to obtain the best loop. Usually, it is not possible to exclude all artefacts completely, but they can be significantly reduced using balancing and triggering. After saving a BH-loop, rename the file because it will be rewritten during next single mode run.

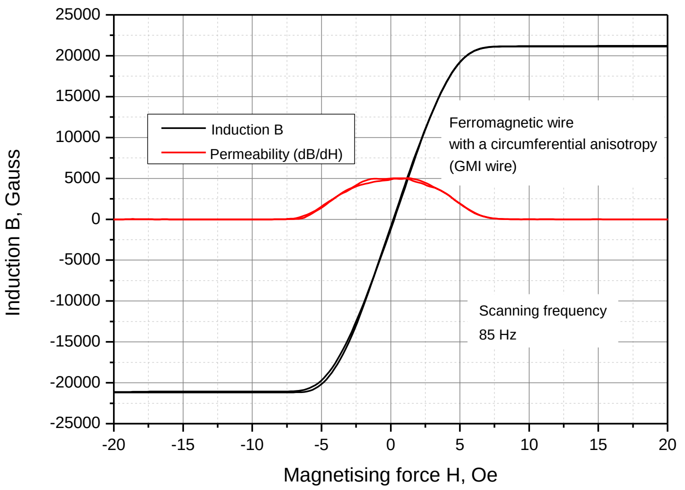
4) Analysis of BH-loops

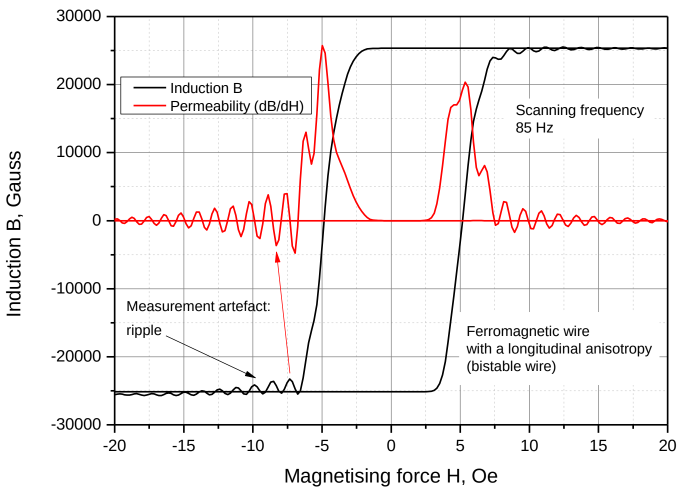
A standard analysis of a BH-loop is shown below (see, for example, https://en.wikibooks.org/wiki/Electronics/Transformer_Design).



The operation of BH-meter was tested for two glass-coated ferromagnetic wires with circumferential and longitudinal anisotropies (see below). The scanning frequency was 85 Hz. The pickup coils were balanced both mechanically and electronically. A trigger level was applied to eliminate openings at the saturation levels. The wire with a circumferential anisotropy (GMI wire) demonstrates almost no artefacts, while for the wire with a longitudinal anisotropy a ripple at the saturation levels could not be avoided (probably due to unperfect balancing). The ripple becomes even more pronounced when calculating the permeability (first derivative dB/dH). However, these artefacts do not complicate the analysis because all necessary characteristics are easily retrieved: type of anisotropy, coercivity, anisotropy field (for GMI wire), saturation magnetisation, and maximum permeability. Magnetic losses can be calculated from the area of the BH-loop.

Measurements with a pair of differential pickup coils cannot predict how the induction approaches the saturation – it is a choice of the operator. By balancing the coils, one can always set a certain slope of the curves. In the graphs below, we chose the horizontal saturation levels. In most cases, it is possible to predict the shape of the curves approaching the saturation depending on expected magnetic properties. Also eliminating artefacts by balancing the pickup coils may prompt the correct shape of the curves at the saturation.



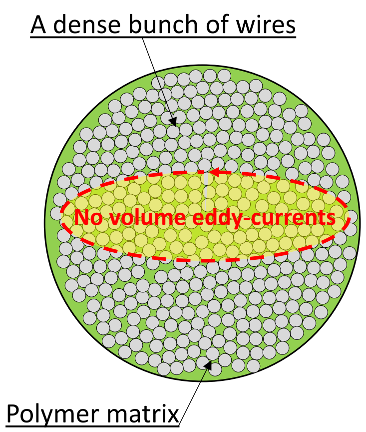


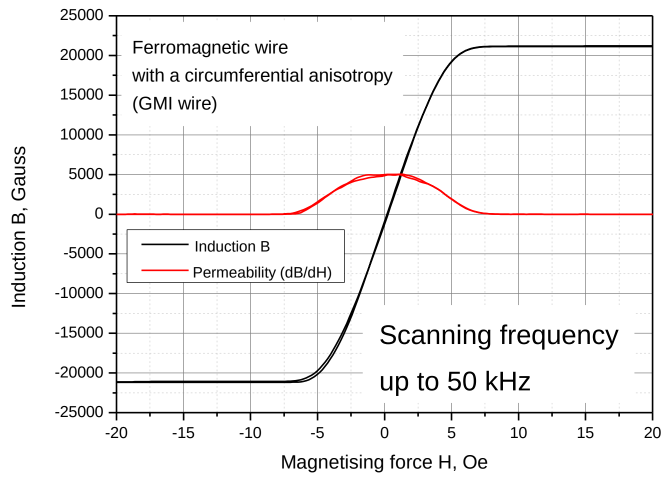
Measurement of high frequency (kHz) BH-loops will require the LC-resonance excitation scheme with a compensating capacitor connected in series with the Helmholtz coil. The program interface and measurement procedure, including the coil balancing, remain the same. The resonance measurement scheme will be explained in the main design report.

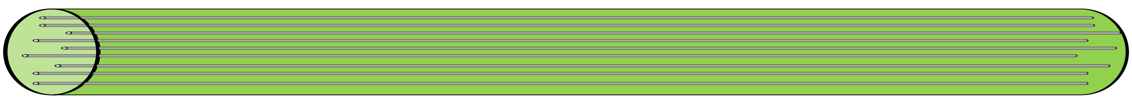
In cgs system of units, the magnetic material equation is $B = H + 4\pi M$. Though all three quantities in this equation have the same dimension, its name is different for three quantities: magnetisation B (G, Gauss), magnetising force H (Oe, Oersted), and magnetisation M (emu×cm^{-3}). Since $B >> H$ for ferromagnetic materials, B can be easily recalculated into M by dividing it by 4π.

Proposal for an industry collaboration project on high frequency composite magnetic cores

A more specific analysis of BH-loops may be required when developing a practical application. In the context of our field of research, it would be interesting to explore the potential of glass-coated ferromagnetic wires for designing high frequency (kHz) composite magnetic cores. A possible composite structure is shown schematically below. It consists of a dense bunch of glass-coated ferromagnetic wires with a circumferential anisotropy embedded into a polymer matrix (host material). The advantage of this magnetic composite structure is the absence of volume eddy-currents and, as result, reduced losses associated with them, while maintaining strong magnetic properties due to the wire alloys with large permeability. Using our NI DAQ 9215, which has the maximum sampling rate 100 kHz, we could measure BH-loops with the scanning frequency up to 50 kHz.







Project objectives:

1) Reviewing the literature on the magnetic core designs with applications to high frequency transformers and switching-mode converters:
   a. Magnetic alloys used for the cores
   b. Material and design parameters of interest
   c. Industry standards and testing techniques
2) Ordering/fabricating glass-coated ferromagnetic wires with different alloy compositions
3) Developing the fabrication technologies for the composite magnetic cores:
   a. Filling the moulds with polymers and wires
   b. Creating the magnetic fibres for 3D printing by means of coating of glass-coated ferromagnetic wires with a polymer

4) Fabricating the composite magnetic cores and measuring their high frequency BH-loops (up to 50 kHz)
5) Analysing BH-loops of the composite magnetic cores in accordance with the industry standards
6) Establishing industry collaborations (in the case of success)

The project could be performed by an undergraduate student. Duration period up to 6 months, including the final report.

Introduction to the design project

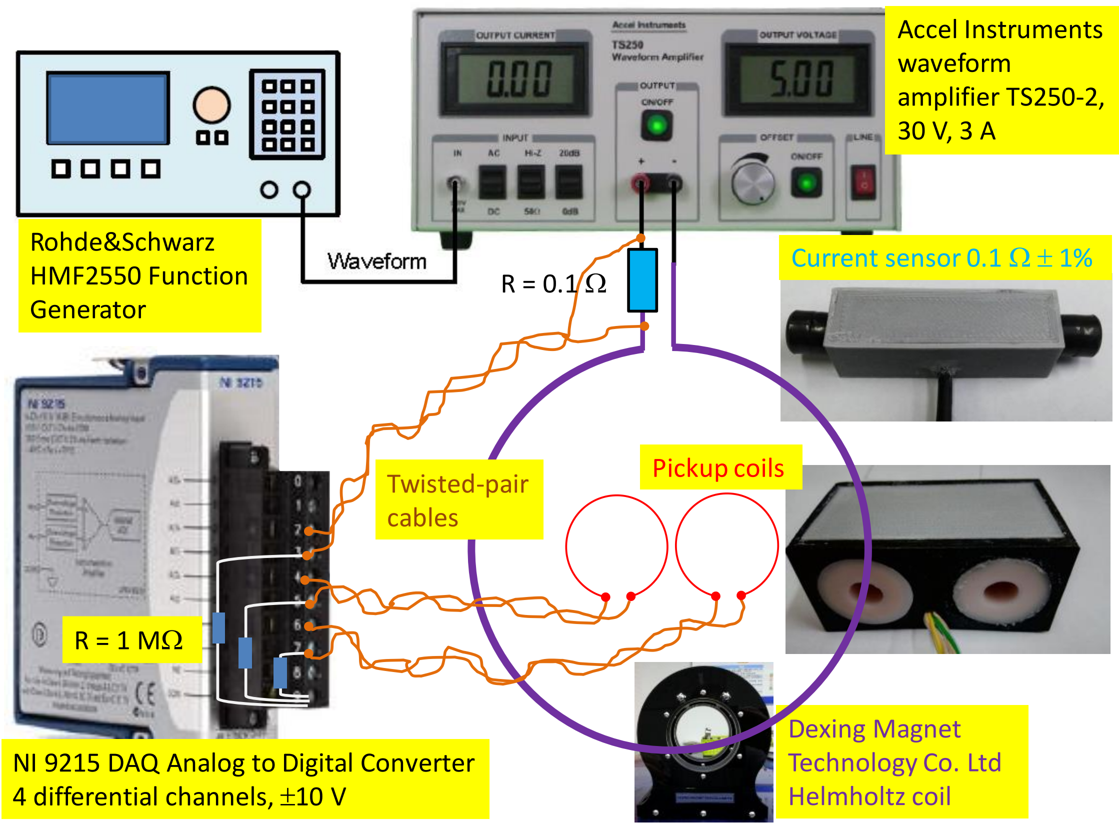
The present project has to be attributed to the instrumental physics where engineers implement already known physical principles for designing new devices and measurement techniques. Directly in this area, discoveries are usually not expected. However, to make a discovery, one needs a device or measurement technique. Thus, although this subject area is auxiliary to scientific exploration, its role in the natural sciences is very important.

Due to a huge variety of possible measurement conditions, creation of a universal BH-meter is hardly possible. That is why many research groups are trying to develop their own BH-meters for particular applications. Any BH-meter based on the Faraday's induction principle will include a scanning magnetic coil (Helmholtz or solenoid) and a pair of identical pickup coils. Other design features may significantly vary depending on the measurement scheme chosen – analog or digital, and also additional functions, for example, measuring hysteresis loops at different temperatures or in the presence of mechanical stress. Now, a common trend in instrument making is the widespread use of digital devices, programming, and numerical analysis. In our project, we managed to completely avoid the development of electronic circuits because NI DAQ analog-to-digital converter (ADC) had sufficient sensitivity to detect weak signals even from a single wire. Synchronous signal readout in the differential channels of ADC made it possible to avoid any external differential circuits because the difference between the pickup coil signals was calculated numerically after digitisation. Further signal processing and then drawing of BH-loops were carried out using the graphical programming language LabVIEW and its VIs (Virtual Instruments) – analog of subroutines in classical programming languages.

Measurement setup

The measurement scheme for the digital BH-meter proposed in our project is shown in Fig. 1. In addition to a Helmholtz coil from Dexing Magnet Technology Co Ltd (China) and two bespoke pickup coils, it includes Accel Instruments TS250-2 waveform amplifier, Rohde&Schwarz HMF2550 function generator, bespoke current sensor, and NI DAQ 9215 analog-to-digital converter. The Helmholtz coil is feed with a sinusoidal waveform from the function generator which is passed through the waveform (power) amplifier. The field generated by the Helmholtz coil is directly proportional to the current which is measured through the voltage across the current sensor – 0.1 Ω resistor connected in series with the coil cable. Together with the voltages measured across the pickup coils, we obtain three independent differential channels with floating grounds which are connected to DAQ by the twisted pair cables. The latter reduce the inductive interference from the Helmholtz coil and other external sources. Interference between the channels is negligible because the differential inputs at DAQ has a very high input resistance resulting in a very low current in the twisted pair cables.

All channels are sampled synchronously that allow avoiding an external analog differential circuit. Also, a high amplitude resolution of DAQ allows avoiding any additional amplification stage before the input. When connecting the differential signals with floating grounds to DAQ with the screw terminals, the negative lead of each differential channel must be connected to COM (terminal 9) through a 1 MΩ resistor to keep the voltage source within the common-mode voltage range, as shown in Fig. 1 and with more details in Fig. 2. These 1 MΩ resistors just provide the same potential for all negative leads, without actual current flow through them. If the voltage source is outside of the common-mode range, then DAQ does not read data accurately – random voltage jumps may be observed in the sampled waveforms. We used the differential channels 2-3, 4-5, and 6-7. The differential channel 0-1 was reserved. The terminal 8 is disconnected. To protect the input terminals together with the resistors, NI 9932 backshell kit was used.



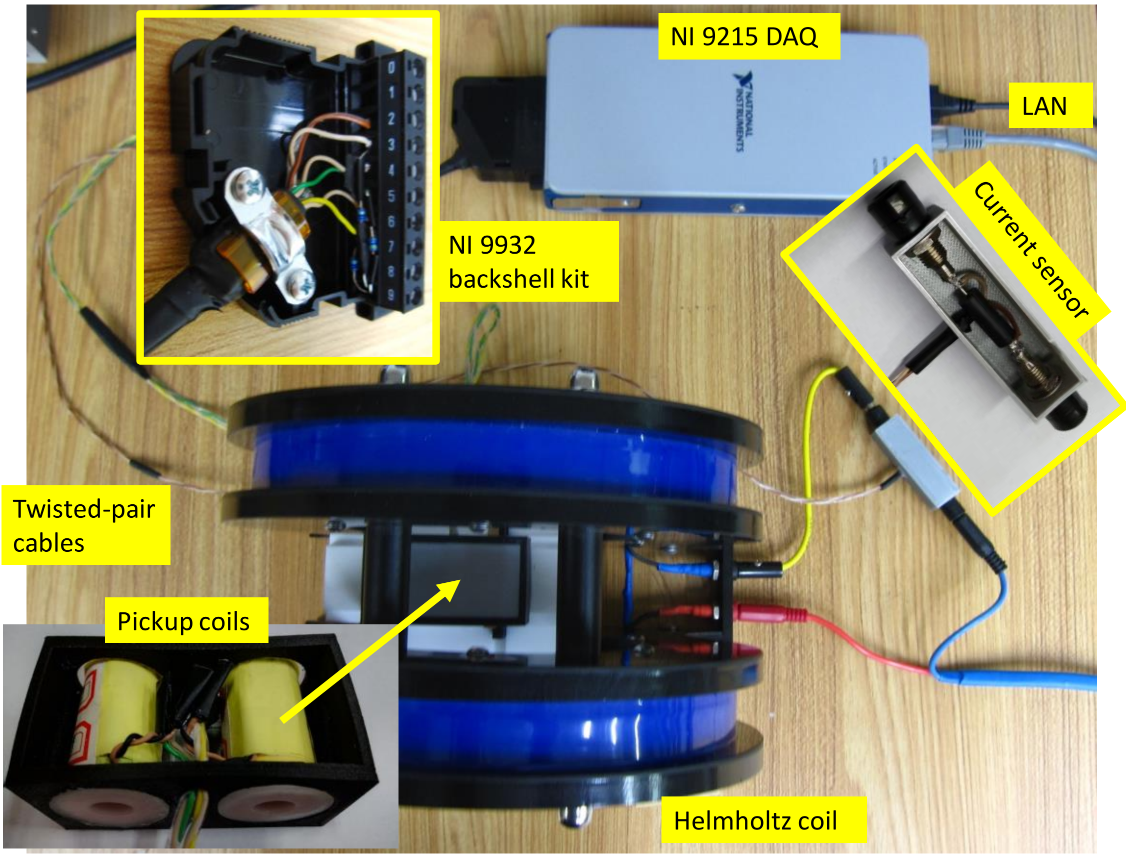


Fig. 1. The measurement scheme and the main constructive elements for the digital BH-meter proposed in our project.

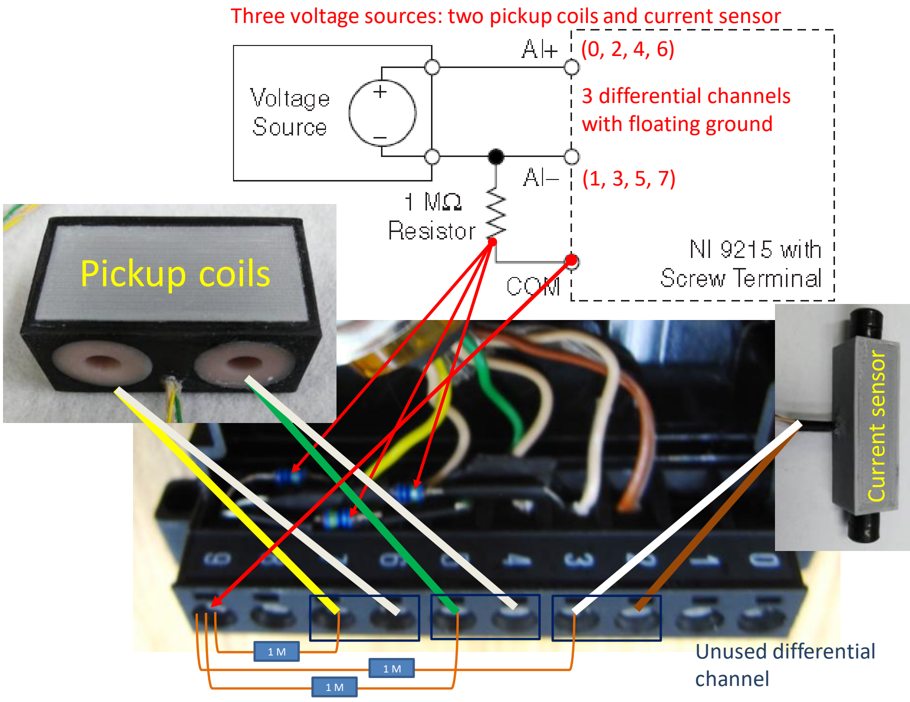


Fig. 2. Connection of the differential channels with floating grounds to the NI DAQ 9215 with screw terminals.

The pickup coils were custom made by Dexing Magnet Technology Co Ltd (China):

- Internal coil diameter – 10 mm
- Length – 30 mm
- Wire diameter together with the enamel coating – 0.087059 mm (copper wire AWG-40)
- Number of layers – 40
- Turns in each layer – 344
- Total number or turns – 13760
- Total diameter (40 layers) – 17 mm

The coils are assumed to be identical, however in reality they never give the same voltage response due to small differences in the winding. The primary amplitude balancing of the signals measured from the pickup coils can be achieved by their slight displacement inside the Helmholtz coil to introduce a compensating difference in the amplitude of alternating magnetic field. To do so, the coil case was placed on a movable platform allowing XY-displacement inside the Helmholtz coil, as shown in Fig. 3. In this regard, a Helmholtz coil is more convenient than a solenoid because it allows easily manipulations with the pickup coils and samples inside. We also provided a digital amplitude balancing of the pickup coils (see user manual). The coil balancing, both mechanical and electronic, is aimed to reduce the differential signal calculated by subtracting two synchronously sampled signals from the pickup coils in the absence of a magnetic sample.

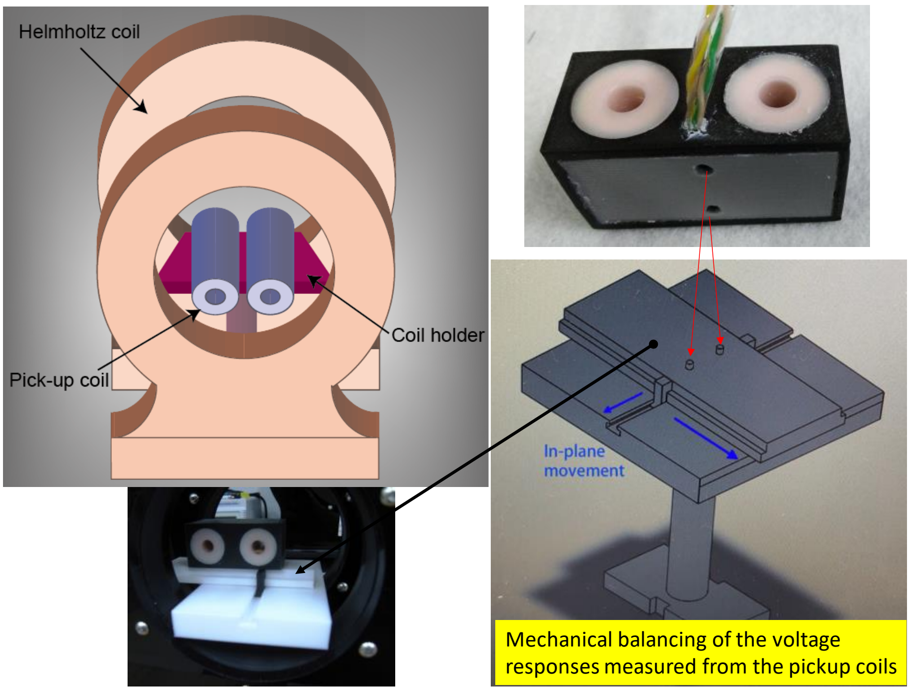


Fig. 3. Movable platform with XY-displacement for the mechanical balancing of the pickup coils.

Physical principles

The external magnetic field, induced by the Helmholtz coil, periodically changes from its minimum negative amplitude to the maximum positive one. The amplitude of the scanning magnetic field is usually chosen to periodically saturate the sample for opposite magnetization directions. The magnetic sample (wire or film) is placed inside one of the pickup coils, as shown in Fig. 4. Before inserting the sample, the coils must be balanced to obtain the minimum differential signal (ground level). The balancing procedure includes the spatial movement of the coils on the in-plane platform (see Fig. 3) and additional electronic balancing using the slide at the front panel of Measurements VI, as explained in the user manual.

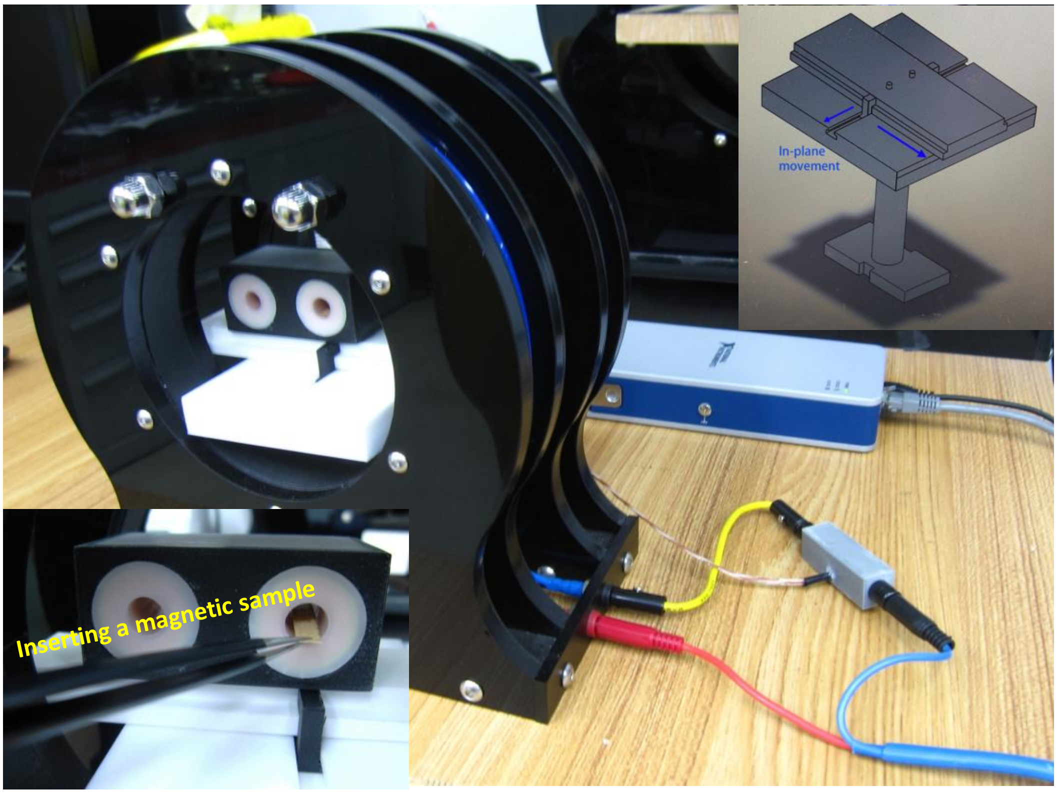


Fig. 4. Inserting a magnetic sample (wire or thin film) into a pickup coil.

According to Faraday's law, the voltage induced in a pickup coil V_p is proportional to the rate of change of the magnetic flux (SI units):

$$V_p(t) = -\alpha \frac{d\Phi(t)}{dt} \quad (1)$$

where Φ is the total flux penetrating the coil opening A_c (area) and α is a structural coefficient taking into account the coil winding. For an empty coil, $\Phi_1(t) = B_0(t)A_c$, where $B_0(t)$ is the magnetic induction which is assumed to be homogeneous across A_c. If a sample inserted, $\Phi_2(t) = B_0(t)(A_c - A_s) + B_s(t)A_s$, where A_s

is the sample cross-section and B_s is the magnetic induction through the sample. For the differential signal calculated from the balanced pickup coils, we obtain:

$$V_d(t) = V_{p2}(t) - V_{p2}(t) = -\alpha \frac{d\left(\Phi_2(t) - \Phi_1(t)\right)}{dt} = -\alpha \frac{d\left(B_0(t)(A_c - A_s) + B_s(t)A_s - B_0(t)A_c\right)}{dt} = \\ = -\alpha \frac{d\left(B_s(t)A_s - B_0(t)A_s\right)}{dt} \tag{2}$$

Since for a magnetic material, $B_s >> B_0$, we finally obtain:

$$V_d(t) \approx -\alpha A_s \frac{dB_s(t)}{dt} \tag{3}$$

To find B_s, the differential voltage $V_d(t)$ must integrated over the time (we are omitting the minus sign which is not important):

$$B_s(t) = \frac{1}{\alpha A_s} \int_0^t V_d(s) ds \tag{4}$$

The magnetising force $H(t)$, induced by the Helmholtz coil, is proportional to the current through it which can be calculated as the voltage measured across the current sensor (see Fig. 1) divided by its resistance 0.1 Ω. Since the sensor voltage (differential channel 2-3) is read synchronously with the pickup voltages (differential channels 4-5 and 6-7), we obtain full synchronisation between the integration by the time variable in (4) and $H(t)$. Drawing $B_s(t)$ against $H(t)$ over a full current period will give a closed BH-loop. The principle (4) is very simple, but its realisation requires a significant technical work, including signal processing algorithms, programming, and the design of pickup coils.

The structural coefficient α can be found from the calibration procedure, where a pickup coil is excited by a long solenoid inserted into it. For the induction inside a long single layer solenoid, we have (SI units):

$$B_0 = \mu_0 n I = \frac{\mu_0 I}{d} \tag{5}$$

where n is the number of turns per unit length, d is the winding wire diameter, $\mu_0 = 4\pi \times 10^{-7}$ H/m is the vacuum permeability, and I is the current through the solenoid. Then, for the voltage induced in the pickup coil, we obtain:

$$V(t) = -\alpha A_{sol} \frac{dB_0(t)}{dt} = -\frac{\alpha A_{sol} \mu_0}{d} \times \frac{dI(t)}{dt} \tag{6}$$

where A_{sol} is the solenoid cross-section.

For a harmonic excitation with the angular frequency ω, we obtain:

$$\begin{cases} V_0 = \dfrac{\alpha A_{sol}\mu_0 I_0 \omega}{d} \\ \alpha = \dfrac{V_0 d}{A_{sol}\mu_0 I_0 \omega} \Rightarrow B_s(t) = \dfrac{1}{\alpha A_s}\int_0^t V_d(s)ds \text{ [Tesla, SI units]} \\ \alpha = \dfrac{V_0 d}{10^4 A_{sol}\mu_0 I_0 \omega} \Rightarrow B_s(t) = \dfrac{1}{\alpha A_s}\int_0^t V_d(s)ds \text{ [Gauss, cgs units]} \end{cases} \quad (7)$$

where V_0 is the pickup voltage amplitude and I_0 is the solenoid current amplitude. The design of calibration solenoid is shown in Fig. 5. A 100 Ω series resistor was included into the solenoid circuit to limit the current amplitude that was monitored by means of the same 0.1 Ω current sensor, as shown in Fig. 6. For the future solenoid designs we suggest using a higher resistor for the current sensor, say 100 Ω. Then, the series resistor in Fig. 6 becomes unnecessary. With the design in Fig. 6, the maximum voltage amplitude across the 0.1 Ω current sensor was just about 6 mV: $0.1\times 10/(100+50+16)$, where 10 V is the maximum generator voltage, 50 Ω is the generator output resistance, and 16 Ω is the solenoid resistance. Such small voltage amplitude was quite noisy. Though it is an obvious observation, we missed this point when making the solenoid, but fortunately it was not a critical mistake.

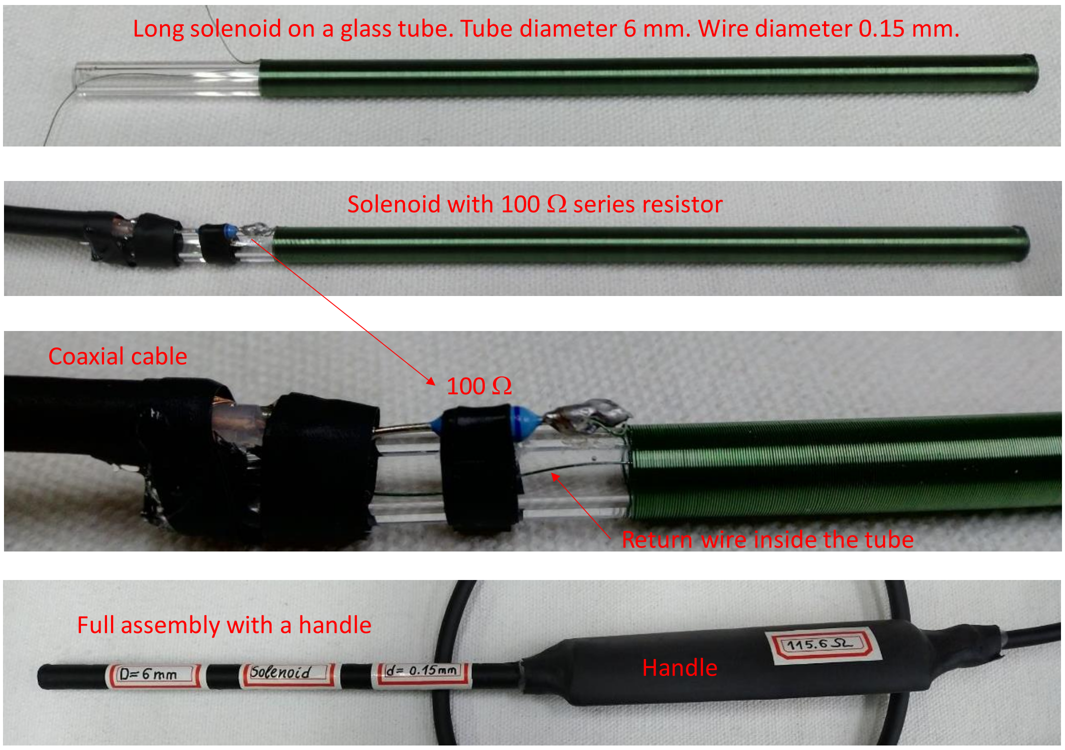


Fig. 5. Design of the calibration solenoid, single layer, turn to the turn.

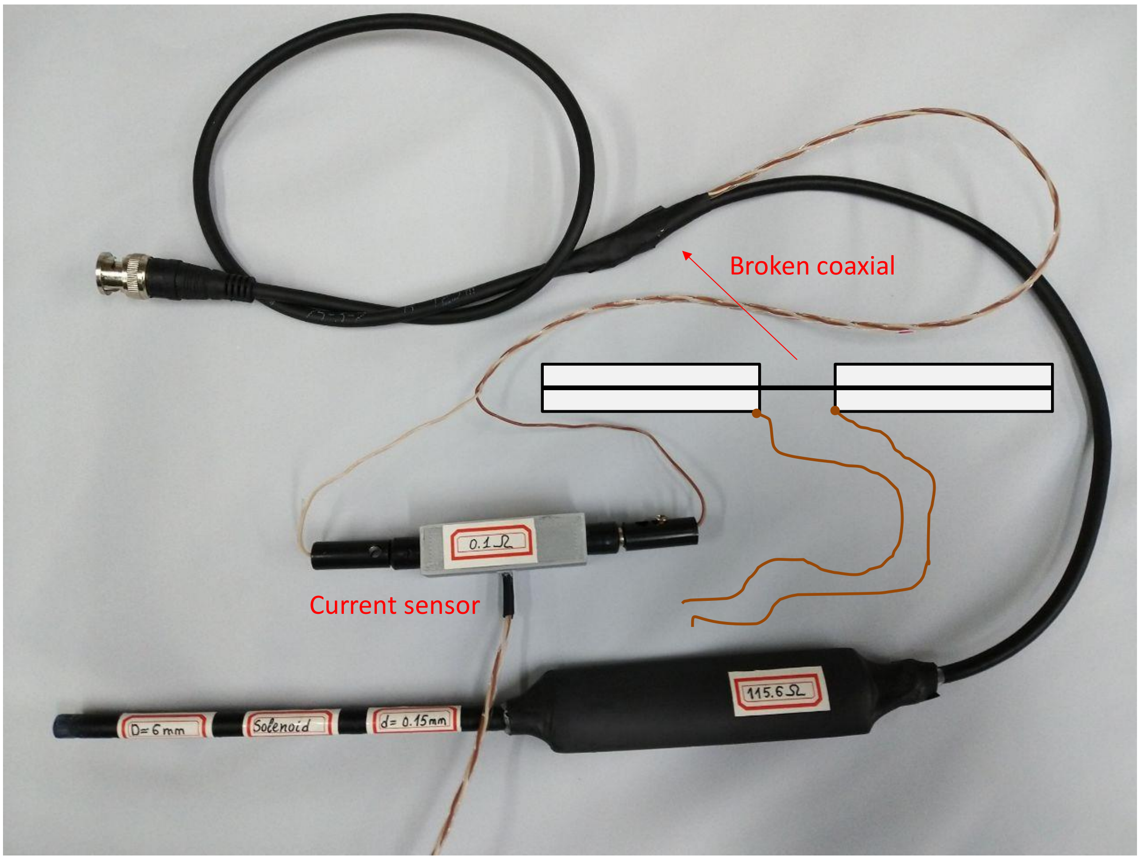


Fig. 6. Assembled calibration solenoid with the current monitoring.

The solenoid was inserted into one of the pickup coils (see Fig. 7) and connected by its coaxial cable to the HMF function generator providing a sinusoidal excitation. The coefficient α in (7) was determined for different frequencies below several kHz and then averaged. Theoretically, α must be constant for any frequency. However, in experiment we observed small variations, probably due to the noisy voltage output from the current sensor.

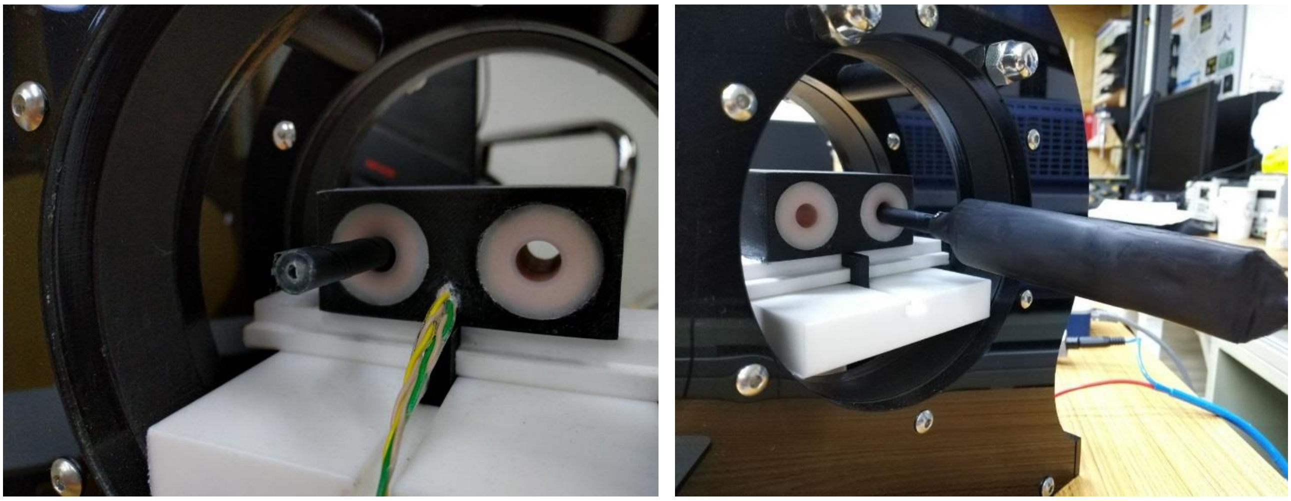
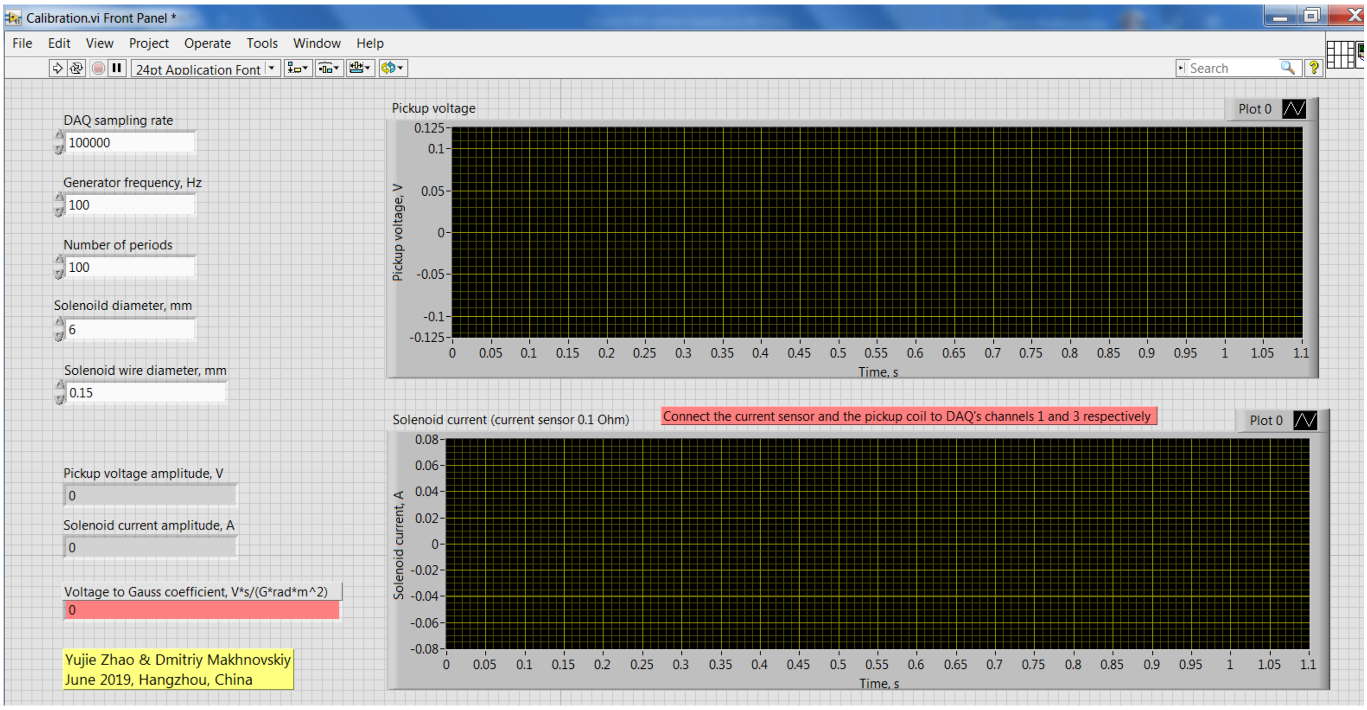
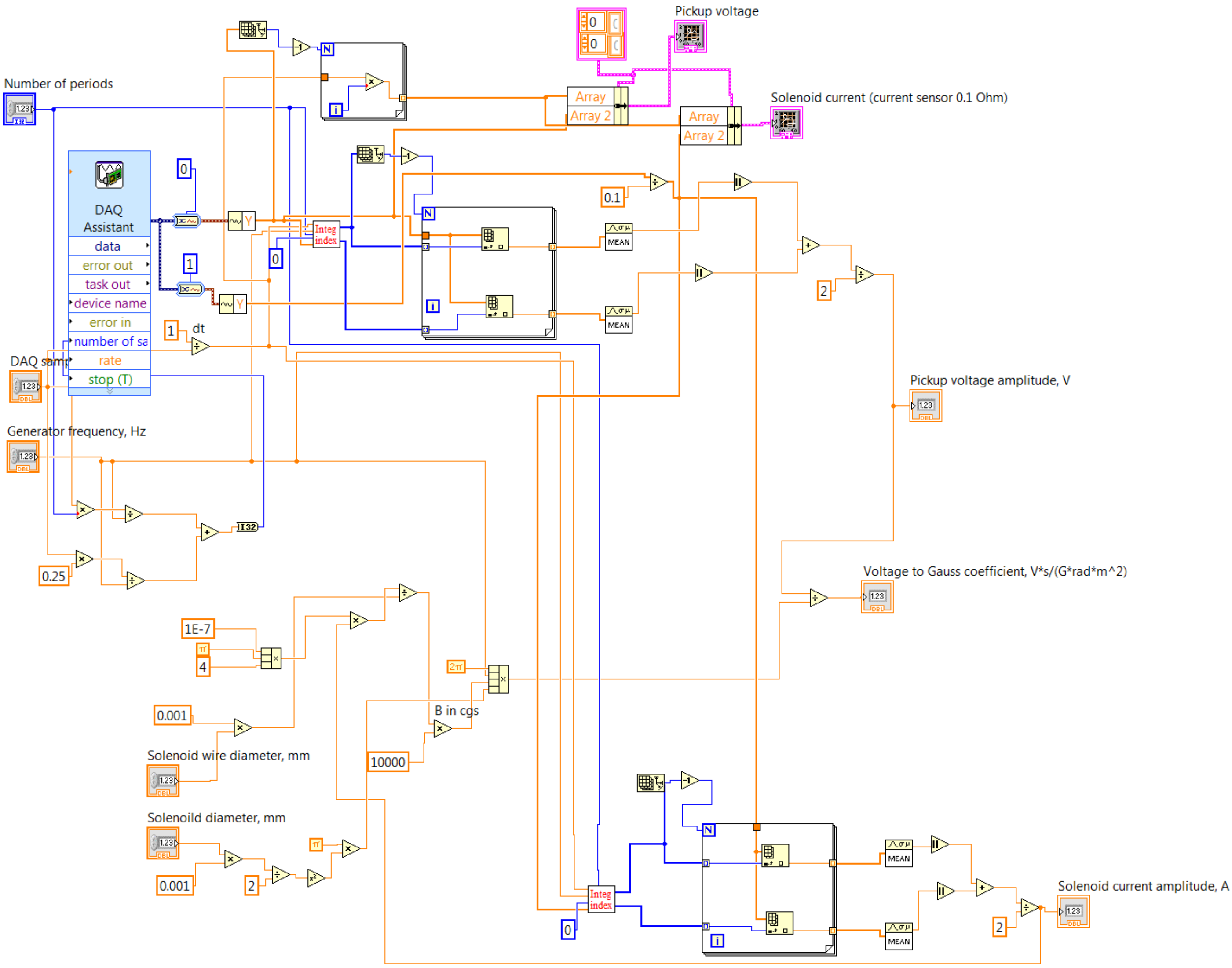


Fig. 7. Calibration solenoid inserted into a pickup coil.

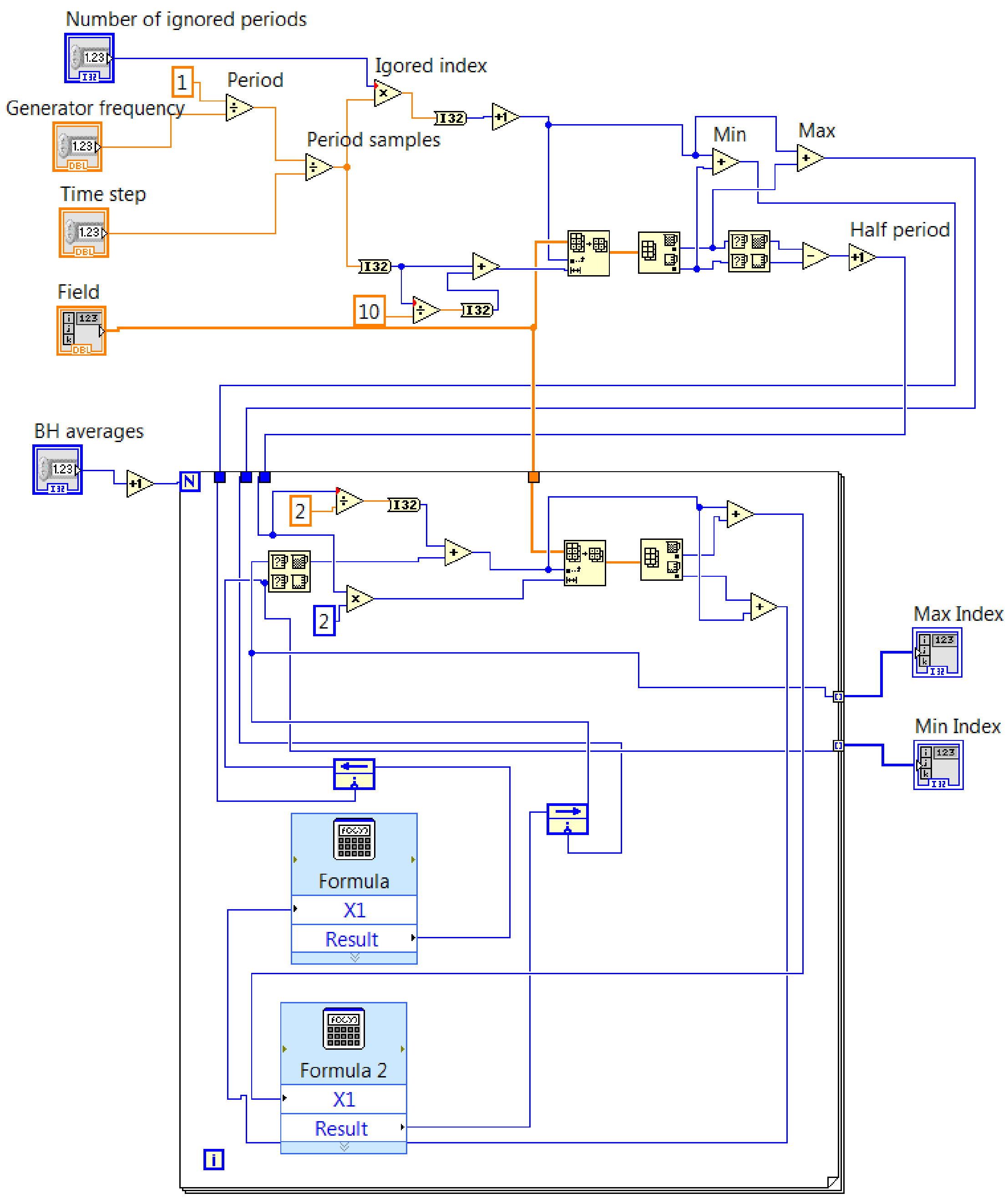
The pickup coil and the current sensor were connected to DAQ. To measure V_0 and I_0 for (7), we wrote a LabVIEW VI, interface and algorithm of which are shown below. It consists of the main **Calibration VI** and the subroutine **Integ_index VI**. The program does not drive the function generator. The generator voltage (up to 10 V) and frequency must be chosen manually at the generator (device) front panel. Then, the chosen frequency must be specified at the program front panel. When running Calibration VI (continuous or single mode), DAQ synchronously reads two arrays of the sinusoidal voltage outputs from the pickup coil and the current sensor. The length of arrays is defined by the number of periods specified on the program front panel. The voltage array from the current sensor is recalculated into the current array by dividing by 0.1 Ω. Then, each array is passed to the independent Integ_index VI that finds indexes of the maximums and minimums of the periodical responses (more detailed explanations will be provided in next section). These indexes are saved as two integer arrays. Using these indexes, Calibration VI chooses the maximum and minimum values in the voltage and current arrays and calculates separate mean values for them: $\bar{V}_{\min} = \frac{1}{N}\sum_{i}^{N} V_{\min i}$, $\bar{V}_{\max} = \frac{1}{N}\sum_{i}^{N} V_{\max i}$, $\bar{I}_{\min} = \frac{1}{N}\sum_{i}^{N} I_{\min i}$, $\bar{I}_{\max} = \frac{1}{N}\sum_{i}^{N} I_{\max i}$. The final voltage and current amplitudes for (7) are calculated as $V_0 = \left(|\bar{V}_{\min}| + |\bar{V}_{\max}|\right)/2$ and $I_0 = \left(|\bar{I}_{\min}| + |\bar{I}_{\max}|\right)/2$, thus automatically compensating a possible DC offset in the read data. For the manufactured pickup coils, we obtained $\alpha \approx 1.2$ (V×s/(G×rad×m^2)) for recalculating the integrated voltage in (4) into the magnetic induction in Gauss (cgs units).



Calibration VI



Integ index VI used in Calibration VI



Measurement and signal processing algorithms

Measurement and signal processing algorithms were realised in LabVIEW graphical programming language. The program structure is shown in Fig. 8. We created six VIs: **Measurements**, **GroundRemoval**, **Channels**, **Spline_interp**, **TimeDelay**, and **Integ_index**. In addition to them, the program includes many other VIs from LabVIEW library.

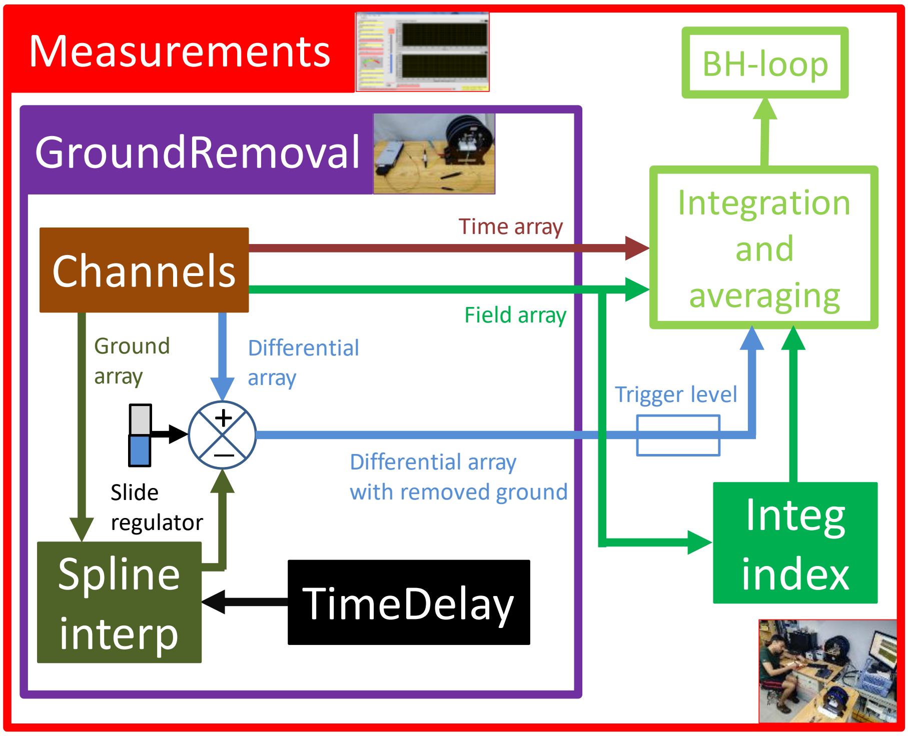
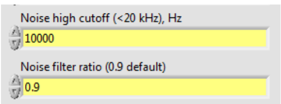


Fig. 8. Structure of LabVIEW program.

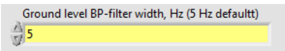
Channels VI

- Reading the voltage signals from two pickup coils and the current sensor and creates the corresponding arrays
- Creating the sampling time array
- Converting the sensor voltage array into the field array
- Applying a low-pass filter to the field array and the differential array, calculated from the pickup coil arrays. This filter cuts off the high frequency noise and introduces a synchronous delay time both to the differential and field signals.



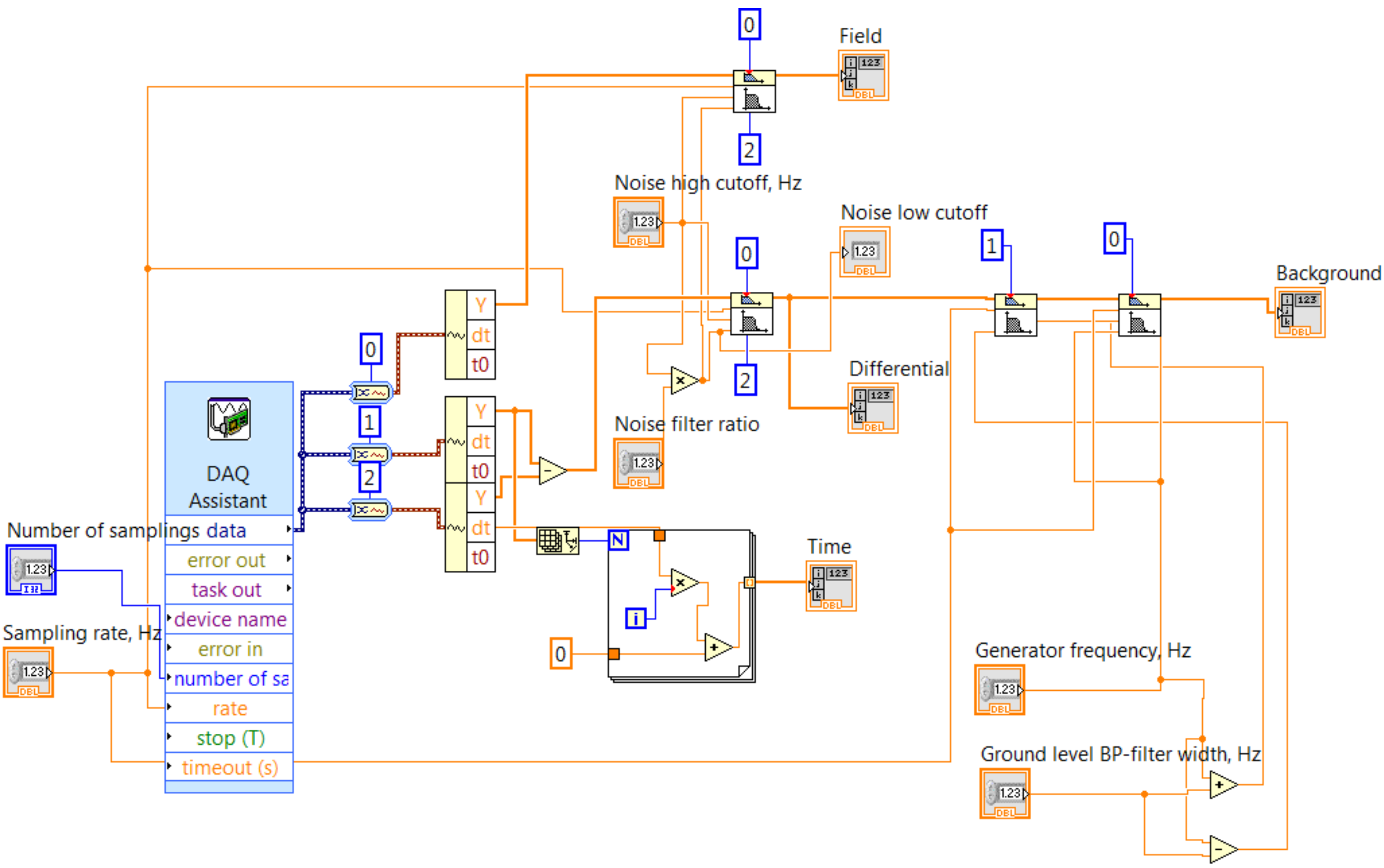
(see user manual)

- Applying a narrow band-pass (BP) filter to the differential signal to extract the low frequency ground level noise. The central frequency of the filter equals the generator excitation frequency. The BP-filter consists of low-pass and high-pass filters connected in series.



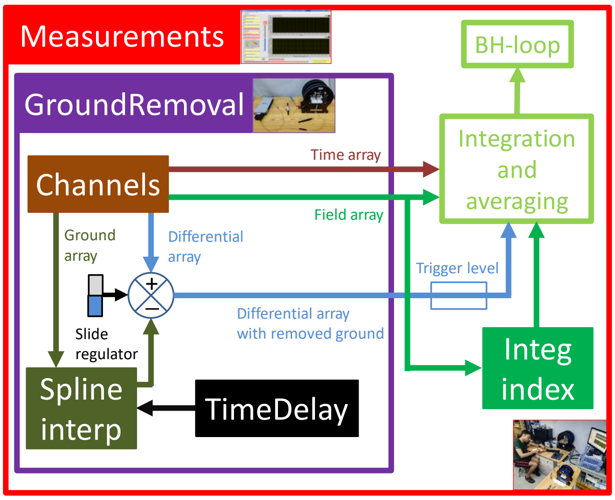
(see user manual)

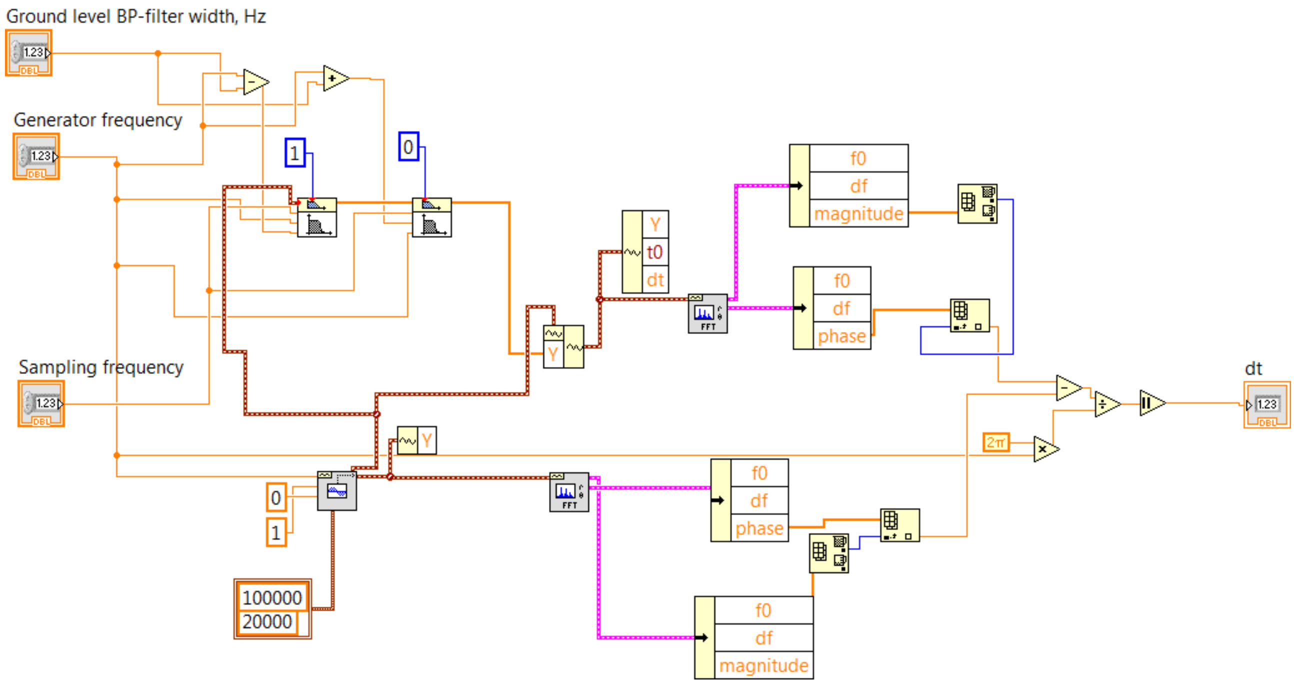
- Creating the ground level array (after BP-filter).



TimeDelay VI

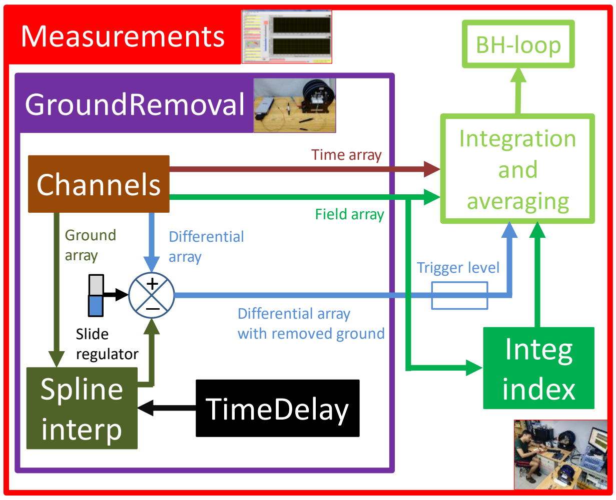
- Calculating the delay time Δt introduced by the BP-filter (used to extract the ground level low frequency noise) by applying a sinusoidal signal with the generator frequency f_g, and then calculating the phase φ (FFT VI): $\Delta t = \varphi/(2\pi f_g)$.

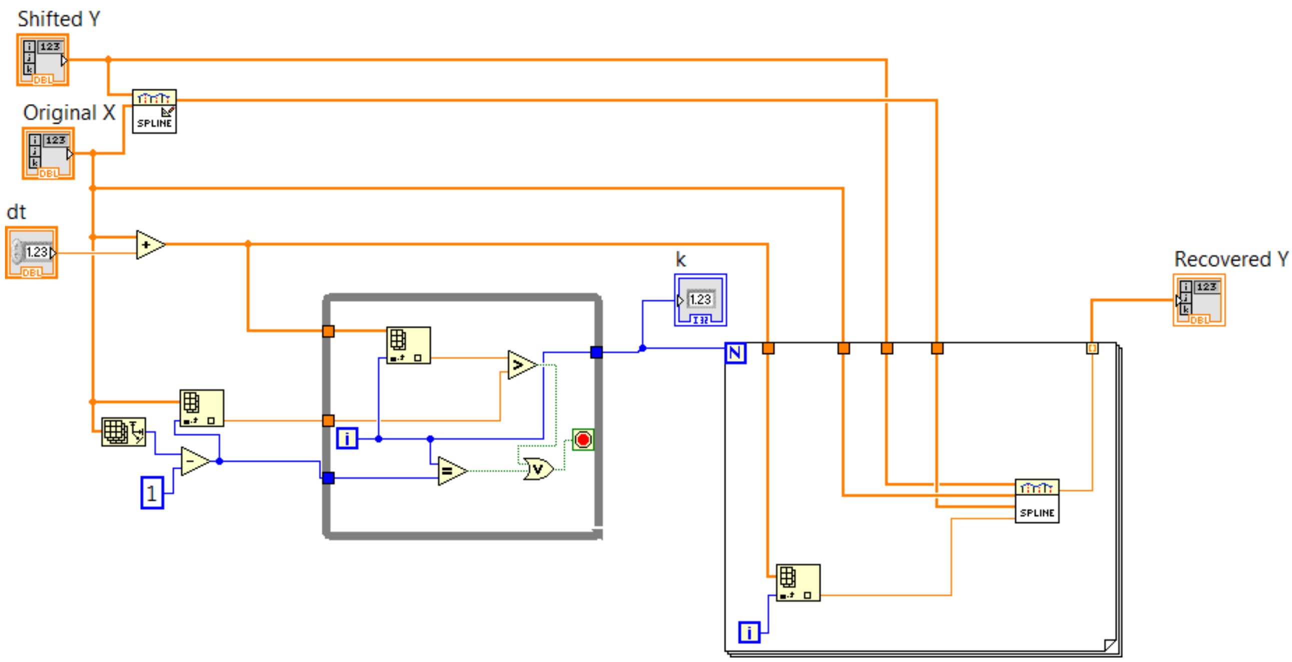




Spline-Interp VI

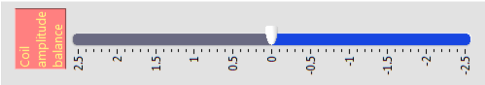
- Spline interpolating the ground level, selected by the BP-filter, and recalculates it for the initial time scale used for the differential and field arrays, thus compensation the delay time introduced by the BP-filter.





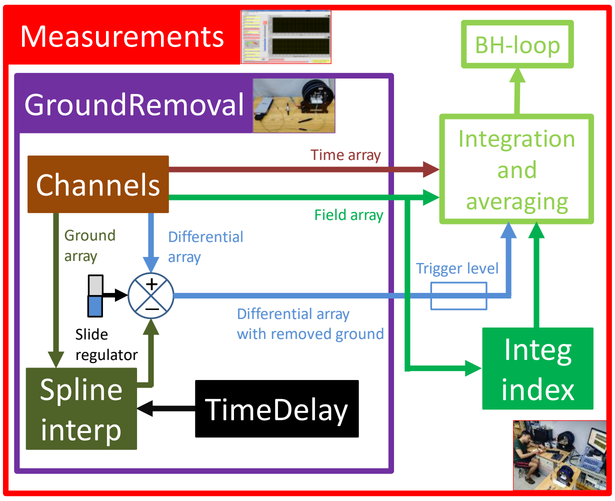
GroundRemoval VI

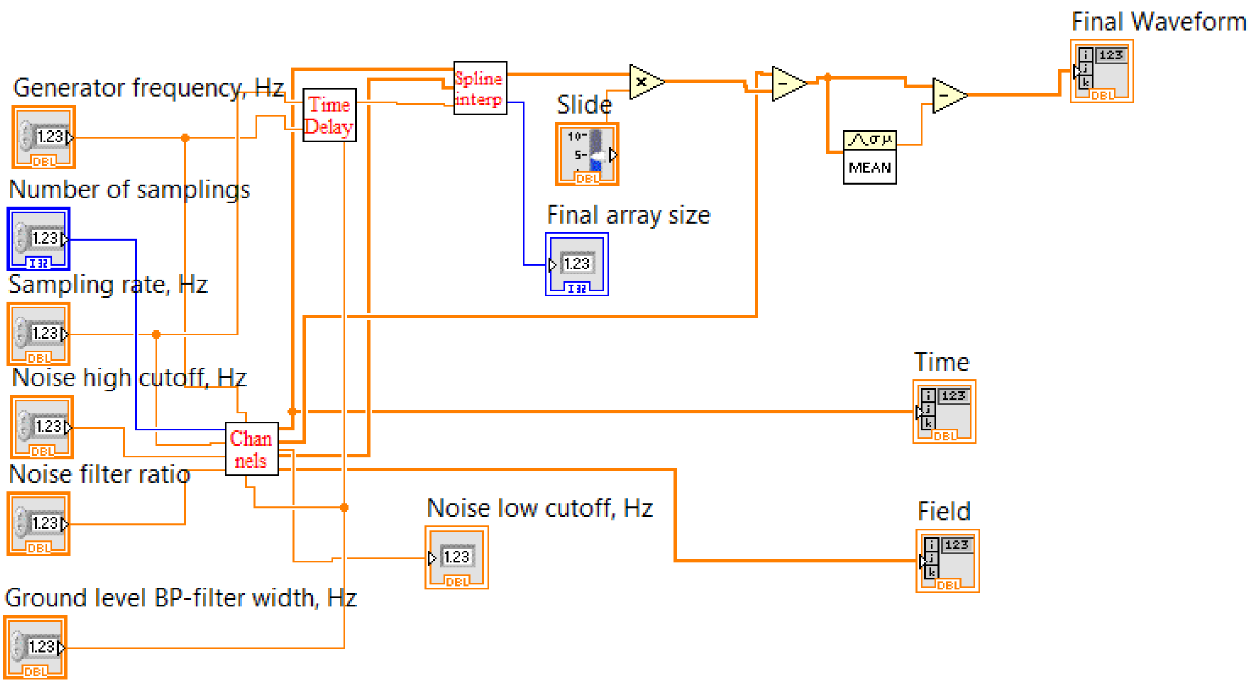
- Subtracting the ground level, including DC offset and low frequency noise, from the differential array, thus forming the final waveform ready for the integration.



(see user manual)

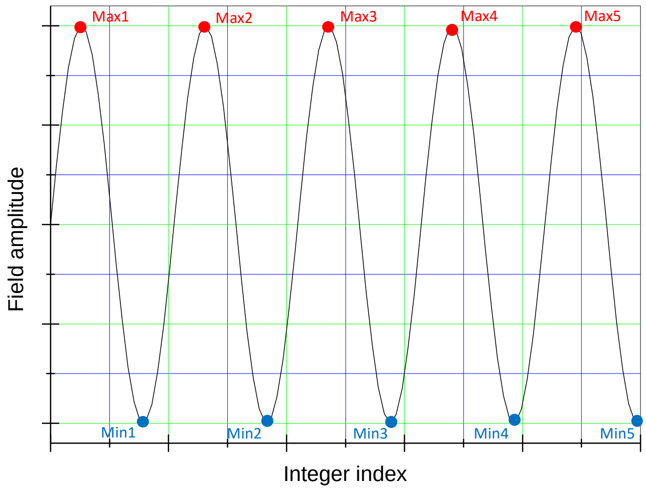
The slide regulator is used to additionally adjust the ground level amplitude before the subtraction. The ground level noise is the main problem when designing an inductive BH-meter because during the integration in (4) a large error may be accumulated. It is not possible to completely remove the ground level noise, but at least it can be significantly suppressed.

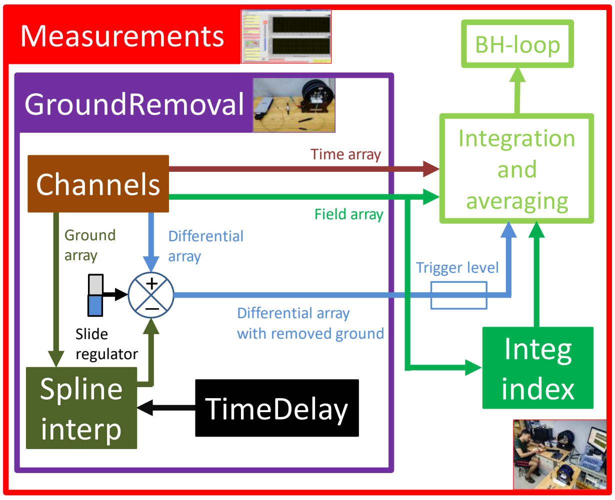


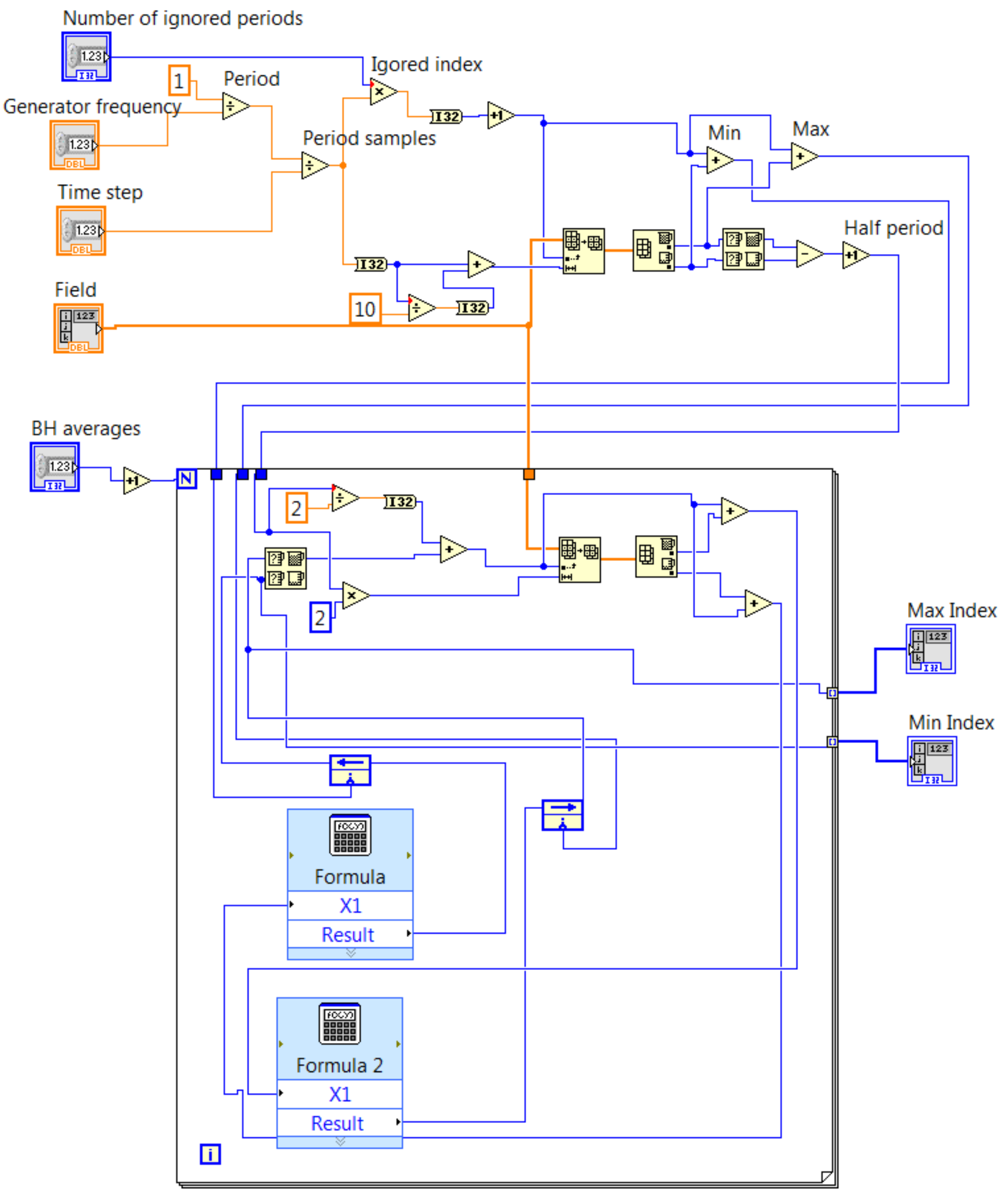


Integ_index VI

- Reading the field array and creating two integer arrays with the indexes that indicate the maximum and minimum field values, as shown below.

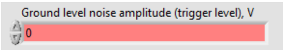






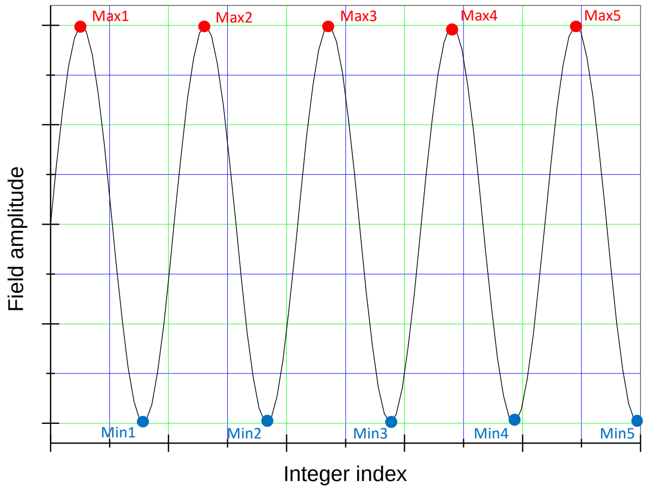
Measurements VI

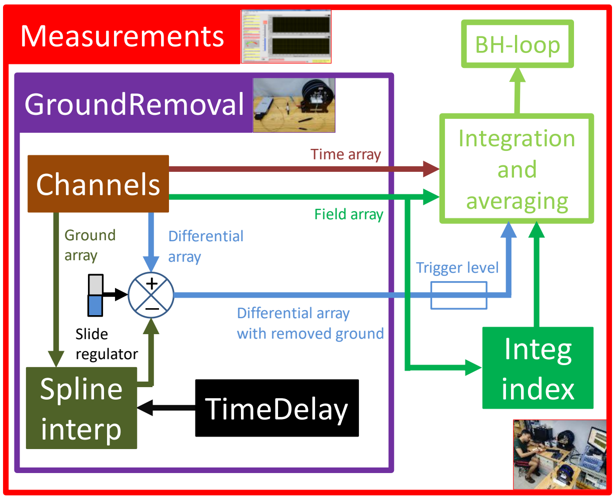
- Integrating the differential arrays, drawing the BH-loop, and saving it to a .csv file. The amplitude triggering can be applied to the differential array before its integration to ground to zero the signal amplitudes which are below the specified level (ground level noise amplitude). The trigger level can be estimated from the amplitude of the low frequency noise after balancing the coils (without sample).

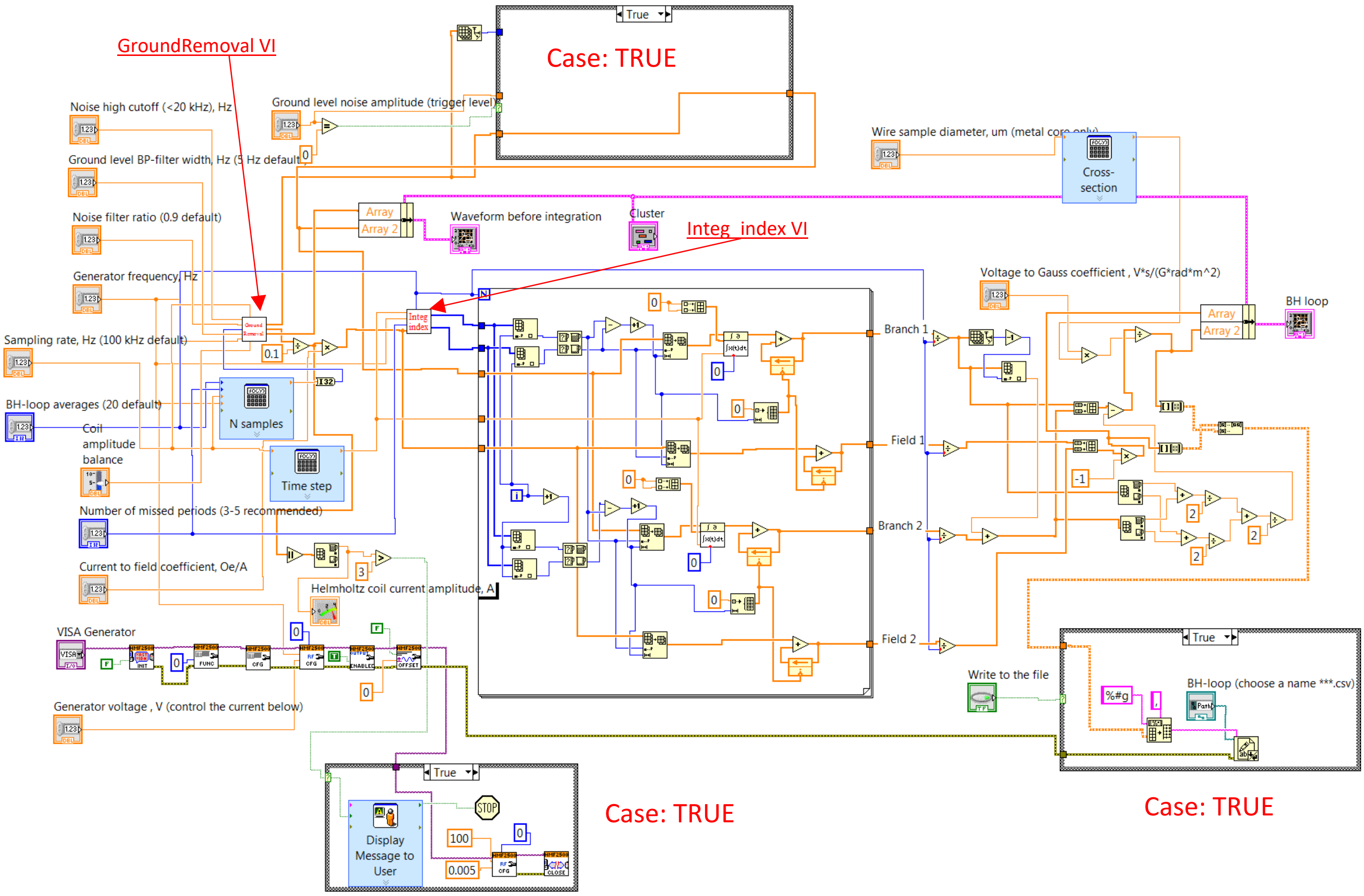


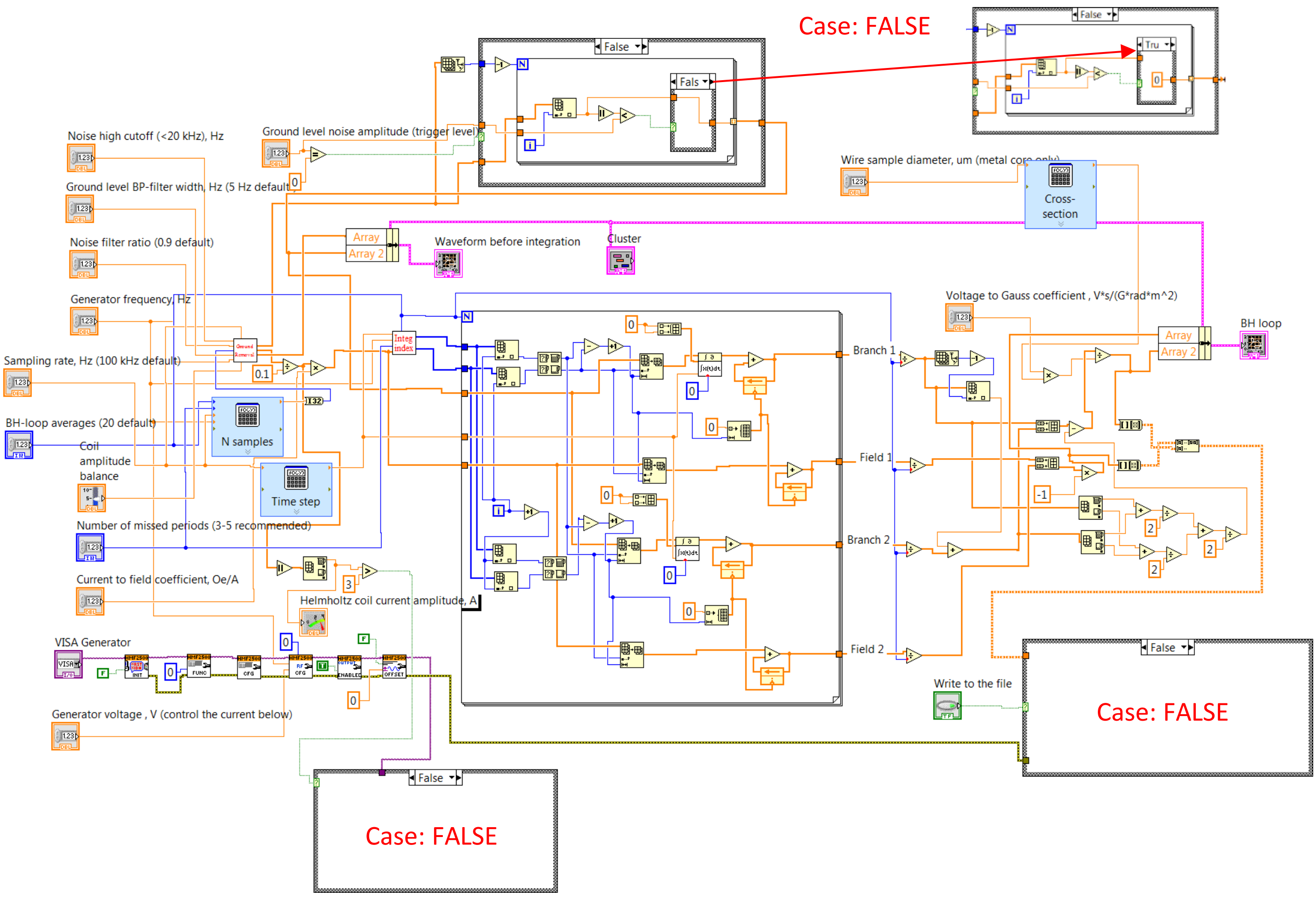
(see user manual)

The forward and reverse branches of a BH-loop are calculated separately over several periods (full field scans) and then averaged. The branches for the integration are selected using the max and min indexes provided by **Integ_Index VI**. The forward BH-branches are obtained, for example, by integrating the differential array (with removed ground level) within the intervals $[\max i, \min i]_{i=1,N+1}$, while the reverse BH-branches within the intervals $[\min i, \max i+1]_{i=1,N}$, where N is the number of the scanning periods. The integration is conducted using the trapezoidal method available as a LabVIEW VI. Then, the results of integration are averaged for each branch. The scanning fields are also averaged for each branch.






GroundRemoval VI
Case: TRUE
Noise high cutoff (<20 kHz), Hz
Ground level noise amplitude (trigger level)
Ground level BP-filter width, Hz (5 Hz default)
Noise filter ratio (0.9 default)
Generator frequency, Hz
Sampling rate, Hz (100 kHz default)
BH-loop averages (20 default)
Coil amplitude balance
N samples
Time step
Number of missed periods (3-5 recommended)
Current to field coefficient, Oe/A
Helmholtz coil current amplitude, A
VISA Generator
Generator voltage , V (control the current below)
Array
Array 2
Waveform before integration
Cluster
Integ_index VI
Wire sample diameter, um (metal core only)
Cross-section
Voltage to Gauss coefficient , V*s/(G*rad*m^2)
BH loop
Branch 1
Field 1
Branch 2
Field 2
Write to the file
BH-loop (choose a name ***.csv)
%#g
Display Message to User
STOP
100
0.005
Case: TRUE
Case: TRUE


Case: FALSE
Noise high cutoff (<20 kHz), Hz
Ground level noise amplitude (trigger level)
Ground level BP-filter width, Hz (5 Hz default)
Noise filter ratio (0.9 default)
Generator frequency, Hz
Sampling rate, Hz (100 kHz default)
BH-loop averages (20 default)
Coil amplitude balance
N samples
Time step
Number of missed periods (3-5 recommended)
Current to field coefficient, Oe/A
Helmholtz coil current amplitude, A
VISA Generator
Generator voltage , V (control the current below)
Array
Array 2
Waveform before integration
Cluster
Wire sample diameter, um (metal core only)
Cross-section
Voltage to Gauss coefficient , V*s/(G*rad*m^2)
BH loop
Branch 1
Field 1
Branch 2
Field 2
Write to the file
Case: FALSE
Case: FALSE

Helmholtz coil parameters

The variable current $I(t)$ passed through the Helmholtz coil induces the magnetising force $H(t)$:

$$H(t) = \beta I(t) \tag{8}$$

where β is a proportionality coefficient. The coil parameters, including its resistance R and inductance L, can be measured using a digital multimeter (DMM), as shown in Fig. 9. The current through the coil is monitored using the 0.1 Ω current sensor connected in series. The voltage across the current sensor is acquired by a DAQ differential channel.

Fig. 9. Measurement of the coil parameters using a DMM.

Pickup coil design for the non-resonant excitation method

In the non-resonant method, the Helmholtz coil (LOAD) is connected directly to the waveform amplifier TS250-2, as shown in Fig. 1. The sinusoidal excitation waveform is supplied by the HMF function generator having the maximum voltage amplitude 10 V at the 50 Ω BNC port. The main parameters of TS250-2:

- Maximum input voltage ±20 V
- Maximum output voltage ±30 V
- Maximum output current amplitudes DC ±2.1 A and AC ±3.0 A
- Maximum operation frequency 75 kHz
- Voltage gains 1 (0 dB) and 10 (20 dB)

For a harmonic excitation voltage $V(t)=V_0\exp(-i\omega t)$, we obtain using (8):

$$H(t)=\frac{\beta V_0\exp(-i\omega t)}{R+i\omega L} \tag{9}$$

where $\omega=2\pi f$ is the angular frequency (rad×s^{-1}; SI units), V_0 is the voltage amplitude (V; SI units), $Z=R+i\omega L$ is the coil impedance (Ω, Ohms; SI units), R is the coil resistance (Ω; SI units), and L is the coil inductance (H, Henry; SI units), i is the imaginary unit. For the selected TS250-2, the maximum amplitude is $V_0=30$ V. For the amplitude of the magnetising force H (SI or cgs units), we obtain:

$$H_0[\mathrm{A}\times\mathrm{m}^{-1}]=\frac{\beta[\mathrm{m}^{-1}]V_0}{\sqrt{R^2+(\omega L)^2}} \tag{10}$$

or

$$H_0[\mathrm{Oe}]=\frac{10^3\beta[\mathrm{Oe}\times\mathrm{A}^{-1}]V_0}{4\pi\sqrt{R^2+(\omega L)^2}} \tag{11}$$

if the excitation coil was calibrated with $\beta[\mathrm{m}^{-1}]$ or $\beta[\mathrm{Oe}\times\mathrm{A}^{-1}]$ respectively (dimensions are shown in the square brackets). Using Faraday's law, for the voltage $v(t)$ induced in a single layer pickup coil, we obtain (SI units):

$$v(t)=-N\frac{d\Phi(t)}{dt}=-\frac{\pi D^2N}{4}\frac{dB(t)}{dt}=-\frac{\pi D^2N\mu_0}{4}\times\frac{dH(t)}{dt}=\frac{\beta\mu_0\pi D^2NV_0\omega}{4(R+i\omega L)}i\exp(-i\omega t) \tag{12}$$

$$v_0[\mathrm{V}]=|v(t)|=\frac{\beta[\mathrm{m}^{-1}]\mu_0\pi V_0\omega}{4\sqrt{R^2+(\omega L)^2}}ND^2 \tag{13}$$

or

$$v_0[\mathrm{V}]=\frac{10^{-4}\beta[\mathrm{Oe}\times\mathrm{A}^{-1}]\pi V_0\omega}{4\sqrt{R^2+(\omega L)^2}}ND^2 \tag{14}$$

where Φ is the magnetic flux through the pickup coil, v_0 is the amplitude of the pickup voltage, N is the number of turns in a single layer, $\mu_0=4\pi\times10^{-7}$ (H×m^{-1}; SI units) is the permeability of vacuum, and D is the coil frame diameter.

For a multilayer pickup coil, the term ND^2 in Eqs. (13),(14) must be modified because for each new layer we will have a slightly different diameter. In addition to D, let us introduce the coil length l (m; SI units), the wire diameter d (m; SI units), and the number of layers N_l. Then, for the number of turns in each layer we obtain: $N=[l/d]$, where the square brackets mean rounding to the integer. Each layer will add an e.m.f. to the total voltage output.

So, instead of D^2 in (13),(14) we have to use the following sum (https://brilliant.org/wiki/sum-of-n-n2-or-n3/):

$$\sum_{n=0}^{N_l-1}(D+nd)^2=\sum_{n=0}^{N_l-1}\left(D^2+2Ddn+n^2d^2\right)=$$
$$=\left(\sum_{n=0}^{N_l-1}D^2+2Dd\sum_{n=0}^{N_l-1}n+d^2\sum_{n=0}^{N_l-1}n^2\right)= \tag{15}$$
$$=N_lD^2\left(1+\frac{d(N_l-1)}{D}+\frac{d^2(N_l-1)(2N_l-1)}{6D^2}\right)$$

Submitting (15) and $N=[l/d]$ into (13),(14), we obtain for the pickup voltage output:

$$v_0[\mathrm{V}]=|v(t)|=\frac{\beta[\mathrm{m}^{-1}]\mu_0\pi V_0\omega}{4\sqrt{R^2+(\omega L)^2}}\left[\frac{l}{d}\right]N_lD^2\left(1+\frac{d(N_l-1)}{D}+\frac{d^2(N_l-1)(2N_l-1)}{6D^2}\right) \tag{16}$$

or

$$v_0[\mathrm{V}]=\frac{10^{-4}\beta[\mathrm{Oe}\times\mathrm{A}^{-1}]\pi V_0\omega}{4\sqrt{R^2+(\omega L)^2}}\left[\frac{l}{d}\right]N_lD^2\left(1+\frac{d(N_l-1)}{D}+\frac{d^2(N_l-1)(2N_l-1)}{6D^2}\right) \tag{17}$$

where $[l/d]N_l$ is the total number of turns in a multilayer pickup coil. Using (15), we can introduce the effective diameter of a multilayer pickup coil that must be used together with the number of turns $[l/d]N_l$:

$$D_{eff}=D\sqrt{1+\frac{d(N_l-1)}{D}+\frac{d^2(N_l-1)(2N_l-1)}{6D^2}} \tag{18}$$

Pickup coil design for the resonant excitation method

In the resonance excitation method, shown in Fig. 10, an additional capacitor C (F, Farad; Si units) is connected in series with the coil to compensate the inductive part of its impedance:

$$Z(\omega) = R + i\left(L\omega - \frac{1}{C\omega}\right) \tag{19}$$

The current resonance condition means that $L\omega_{res} - 1/C\omega_{res} = 0$:

$$\omega_{res} = \frac{1}{\sqrt{LC}} \tag{20}$$

At the resonance, the coil impedance becomes purely real $Z(\omega_{res}) = R$.

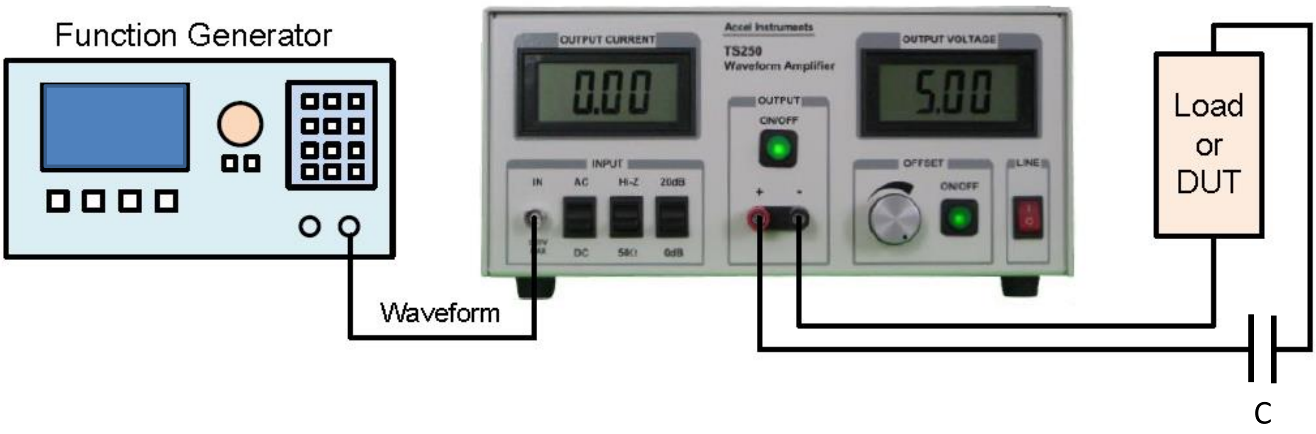


Fig. 10. Resonance excitation method with an additional capacitor connected in series with the coil (inductive load).

Using (16),(17), we obtain at the resonance condition:

$$v_0[\mathrm{V}] = \frac{\beta[\mathrm{m}^{-1}]\mu_0\pi V_0\omega}{4R}\left[\frac{l}{d}\right]N_l D^2\left(1 + \frac{d(N_l - 1)}{D} + \frac{d^2(N_l - 1)(2N_l - 1)}{6D^2}\right) \tag{21}$$

or

$$v_0[\mathrm{V}] = \frac{10^{-4}\beta[\mathrm{Oe}\times\mathrm{A}^{-1}]\pi V_0\omega}{4R}\left[\frac{l}{d}\right]N_l D^2\left(1 + \frac{d(N_l - 1)}{D} + \frac{d^2(N_l - 1)(2N_l - 1)}{6D^2}\right) \tag{22}$$

Other quantities at the resonance condition:

$$H_0[\mathrm{A}\times\mathrm{m}^{-1}] = \frac{\beta[\mathrm{m}^{-1}]V_0}{R} \tag{23}$$

or

$$H_0[\mathrm{Oe}] = \frac{10^3 \beta[\mathrm{Oe} \times \mathrm{A}^{-1}] V_0}{4\pi R} \quad (24)$$

$$V_C = \frac{V_0}{RC\omega_{res}} = \frac{V_0 L \omega_{res}}{R} \quad (25)$$

$$C = \frac{1}{L\omega_{res}^2} \quad (26)$$

where V_C is the voltage amplitude across the capacitor. The magnitude of V_C is important for selecting the proper voltage rate (kV) of the capacitor.

Selection of the pickup coil parameters

The algorithm in Fortran used for analysing the performance of the excitation and pickup coils is shown below. It was compiled as a console application (PickupCoil.exe) and combines all equations derived in the previous two sections.

Fortran code

```
INTEGER flag,i,N,Nl
DOUBLE PRECISION pi,R,L,V0,v,vind,vres,maxf,f,df,mu0,Z,Iex
DOUBLE PRECISION VC,C,a,H1,H2,D,lc,dw,startfres,stopfres
PARAMETER(pi=3.1415926535897932384626433832795, N=5000)

mu0=4.0*pi*1.0E-7

WRITE(*,*)'Enter the resistance of the excitation coil (Ohm).'
READ(*,*) R
WRITE(*,*)''

WRITE(*,*)'Enter the inductance of the excitation coil (mH).'
READ(*,*) L
WRITE(*,*)''
L=L*1.0E-3

WRITE(*,*)'Enter the diameter of the pickup coil (mm).'
READ(*,*) D
WRITE(*,*)''
D=D*1.0E-3

WRITE(*,*)'Enter the length of the pickup coil (mm).'
READ(*,*) lc
WRITE(*,*)''
lc=lc*1.0E-3

WRITE(*,*)'Enter the wire diameter used in the pickup coil (mm).'
READ(*,*) dw
WRITE(*,*)''
dw=dw*1.0E-3

WRITE(*,*)'Enter the number of layers in the pickup coil.'
READ(*,*) Nl
WRITE(*,*)''
```

```
      WRITE(*,*)'Enter the amplitude of the excitation voltage (V).'
      READ(*,*) V0
      WRITE(*,*)''

      WRITE(*,*)'Enter the maximum excitation frequency (Hz).'
      READ(*,*) maxf
      WRITE(*,*)''

      WRITE(*,*)'Enter the start resonance frequency (Hz).'
      READ(*,*) startfres
      WRITE(*,*)''

      WRITE(*,*)'Enter the stop resonance frequency (Hz).'
      READ(*,*) stopfres
      WRITE(*,*)''

      df=maxf/N
      OPEN(10,FILE='Excitation_coil_impedance.CSV')
      WRITE(10,*)'Hertz',',','Ohm'
      DO i=0,N
        f=df*i
        Z=DSQRT(R**2+(2.0*pi*f*L)**2)
        WRITE(10,100) f,Z
      END DO
      CLOSE(10)
100   FORMAT(F20.8,',',F20.8)

      df=(stopfres-startfres)/N
      OPEN(20,FILE='Resonance_capacitor.CSV')
      WRITE(20,*)'Hertz',',','Farad',',','V across C'
      DO i=0,N
        f=startfres+df*i
        C=1.0/(L*(2.0*pi*f)**2)
        VC=V0*L*2.0*pi*f/R
        WRITE(20,200) f,C,VC
      END DO
      CLOSE(20)
200   FORMAT(F20.8,',',F20.20,',',F20.8)

      WRITE(*,*)'Units for the coil calibration coefficient H=a*I:'
      WRITE(*,*)'Enter 1 for a[1/m]'
      WRITE(*,*)'Enter 2 for a[Oe/A]'
      READ(*,*) flag
      WRITE(*,*)''


      df=maxf/N

      OPEN(25,FILE='Excitation_current.CSV')
      WRITE(25,*)'Hz',',','A'
      DO i=0,N
        f=df*i
        Iex=V0/DSQRT(R**2+(2.0*pi*f*L)**2)
        WRITE(25,250) f,Iex
      END DO
      CLOSE(25)
250   FORMAT(F20.8,',',F20.8)
```

```
c     *********************************************
         SELECT CASE(flag)

         CASE(1)

         WRITE(*,*)'Enter the coil calibration coefficient (1/m)'
         READ(*,*) a
         WRITE(*,*)''

         df=maxf/N

         OPEN(30,FILE='Scanning_field.CSV')
         WRITE(30,*)'Hz',',','A/m',',','Oe'
         DO i=0,N
           f=df*i
           H1=a*V0/DSQRT(R**2+(2.0*pi*f*L)**2)
           H2=H1*4.0*pi/1000.0
           WRITE(30,300) f,H1,H2
         END DO
         CLOSE(30)
300      FORMAT(F20.8,',',F20.8,',',F20.8)

         OPEN(40,FILE='Pickup_voltage.CSV')
         WRITE(40,*)'Hz',',','vind',',','vres'
         DO i=0,N
           f=df*i
           v=a*mu0*pi*V0*2.0*pi*f*DINT(lc/dw)*Nl*D**2/4.0
           v=v*(1.0+dw*(Nl-1)/D+dw**2*(NL-1)*(2*Nl-1)/(6.0*D**2))
                 vind=v/DSQRT(R**2+(2.0*pi*f*L)**2)
                 vres=v/R
           WRITE(40,400) f,vind,vres
         END DO
         CLOSE(40)
400      FORMAT(F20.8,',',F20.8,',',F20.8)

         CASE(2)

         WRITE(*,*)'Enter the coil calibration coefficient (Oe/A)'
         READ(*,*) a
         WRITE(*,*)''

         df=maxf/N

         OPEN(50,FILE='Scanning_field.CSV')
         WRITE(50,*)'Hz',',','A/m',',','Oe'
         DO i=0,N
           f=df*i
           H2=a*V0/DSQRT(R**2+(2.0*pi*f*L)**2)
           H1=H2*1000.0/(4.0*pi)
           WRITE(50,500) f,H1,H2
         END DO
         CLOSE(50)
500      FORMAT(F20.8,',',F20.8,',',F20.8)
```

```
        OPEN(60,FILE='Pickup_voltage.CSV')
        WRITE(60,*)'Hz',',','vind',',','vres'
        DO i=0,N
          f=df*i
          v=1.0E-4*a*pi*V0*2.0*pi*f*DINT(lc/dw)*Nl*D**2/4.0
          v=v*(1.0+dw*(Nl-1)/D+dw**2*(NL-1)*(2*Nl-1)/(6.0*D**2))
                vind=v/DSQRT(R**2+(2.0*pi*f*L)**2)
                vres=v/R
          WRITE(60,600) f,vind,vres
        END DO
        CLOSE(60)
600     FORMAT(F20.8,',',F20.8,',',F20.8)

        END SELECT

        OPEN(70,FILE='Coil_parameters.txt')
        WRITE(70,*)'Excitation coil resistance (Ohm) = ',R
        WRITE(70,*)'Excitation coil inductance (mH) = ',L*1000.0
        WRITE(70,*)'Excitation voltage amplitude (V) = ',V0
        WRITE(70,*)''
        WRITE(70,*)'*****************************************************'
        WRITE(70,*)''
        WRITE(70,*)'Pickup coil diameter (mm) = ',D*1000.0
        WRITE(70,*)'Pickup coil length (mm) = ',lc*1000.0
        WRITE(70,*)'Pickup coil wire diameter (mm) = ',dw*1000.0
        WRITE(70,*)'Number of layers = ',Nl
        WRITE(70,*)'Turns in each layer = ',DINT(lc/dw)
        WRITE(70,*)'Total turns = ',Nl*DINT(lc/dw)
        WRITE(70,*)'Total diameter (mm) = ',(D+2*NL*dw)*1000.0
        CLOSE(70)

    STOP

    END
```

Non-resonant excitation and low frequency BH-loops up to 300 Hz

The parameters of the pickup coils will be selected for two Dexing Helmholtz coils we already have in the laboratory:

- "Small Helmholtz coil" (shown in the user manual and Fig. 1)
    - $R = 2.5\ \Omega$
    - $L = 18.4\ \text{mH}$
    - $\beta = 21.06\ \text{Oe/A}$
- "Large Helmholtz coil" (used for MI measurements)
    - $R = 8.38\ \Omega$
    - $L = 320\ \text{mH}$
    - $\beta = 39.95\ \text{Oe/A}$

In Fig. 11, the frequency performance of the small Helmholtz coil was calculated for $V_0 = 30$ V (maximum output voltage for the waveform amplifier TS250-2). Up to 200-300 Hz, the small Helmholtz coil can provide enough field strength to scan and saturate ferromagnetic wires we usually use. For frequencies below 85 Hz, the amplifier output V_0 must be reduced to keep the AC current amplitude below 3 A. So, the maximum scanning field will be no more than 63 Oe.

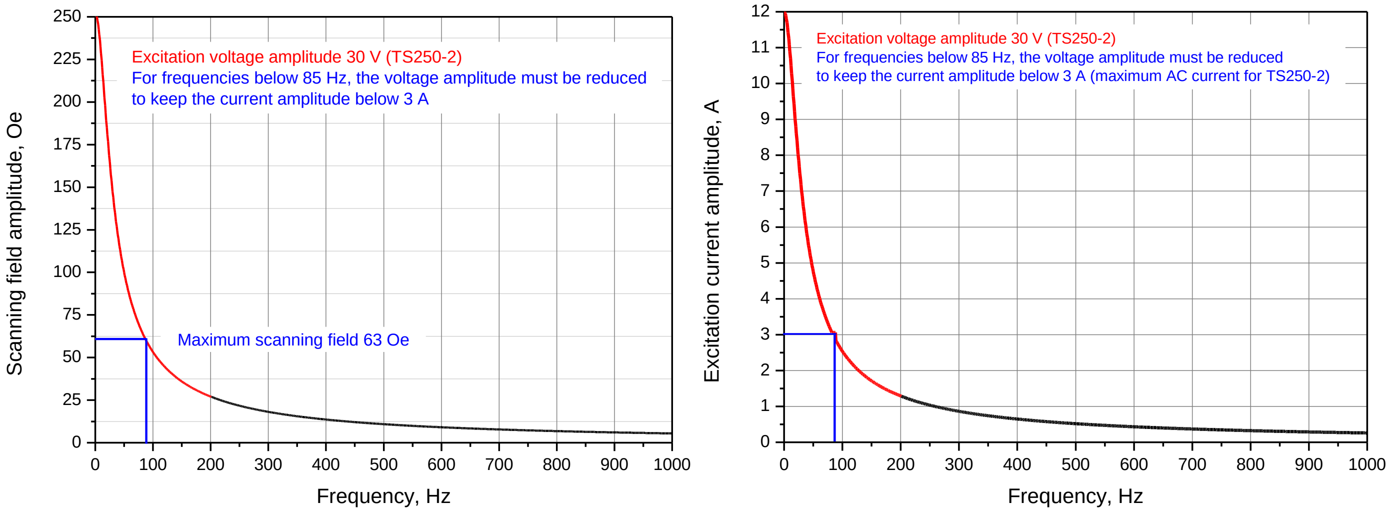


Fig. 11. Frequency performance of the small Helmholtz coil.

At the same time, we must obtain a detectable voltage at the pickup coils. The coil geometrical parameters are dictated by the size of the Helmholtz coil. We chose the following dimensions for the pickup coils:

- Internal coil diameter – 10 mm
- Length – 30 mm

For reasons of the field uniformity inside the Helmholtz coil, the width of the assembly of two pickup coils should not exceed 40 mm. We proposed two sets of the pickup coil parameters with the wire windings made of AWG-38 and AWG-40 (https://en.wikipedia.org/wiki/American_wire_gauge):

Set 1

- Wire diameter together with the enamel coating – 0.109788 mm (copper wire AWG-38)
- Number of layers – 30
- Turns in each layer – 273
- Total number or turns – 8190
- Total diameter (30 layers) – 17 mm

Set 2

- Wire diameter together with the enamel coating – 0.087059 mm (copper wire AWG-40)
- Number of layers – 40
- Turns in each layer – 344
- Total number or turns – 13760
- Total diameter (40 layers) – 17 mm

The pickup voltage amplitudes vs. frequency calculated for these two sets are shown in Fig. 12. Both designs are acceptable, but we should prefer the wire winding made of AWG-40 because it provides a larger voltage output. For AWG-40, we could take even larger number of the coil layers (>40) because DAQ will be saturated for an amplitude span larger than ±10 V, while in Fig. 12 it is only ±5 V. However, when increasing the number of layers, it is necessary to remember about the overall dimensions of the coil assembly (in a case). For the BH-meter realised in the present project, we used Set 2 to manufacture the pickup coils (ordered from Dexing Magnet Technology Co Ltd, China).

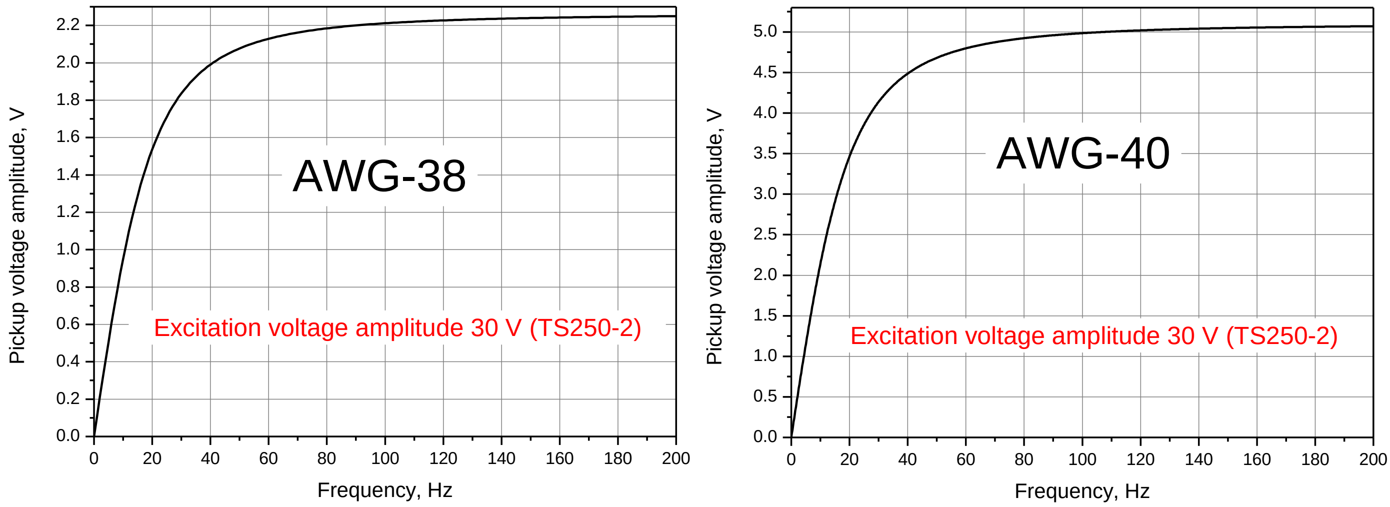


Fig. 12. Pickup voltage amplitudes vs. frequency calculated for two sets of the pickup coil parameters based on the wire windings made of AWG-38 and AWG-40.

Resonance excitation and high frequency BH-loops

To demonstrate the design steps for the resonance excitation scheme shown in Fig. 10, we use the large Helmholtz coil. The amplitude of the excitation voltage must be reduced to $V_0 = 25$ V to guarantee $I = V_0 / R = 25/8.38 \approx 3$ A – maximum current amplitude for the waveform amplifier TS250-2. The coil inductance is 320 mH. Let us start the design looking at the frequency dependence of the voltage amplitude V_C across the capacitor shown in Fig. 13. From this graph, we see that V_C may reach and exceed 50 kV for higher frequencies. So, a high voltage (HV) capacitor will be required for the LC resonance circuit. Potential suppliers of the HV capacitors:

- http://www.avx.com/products/ceramic-capacitors/high-voltage/hdhe-type/
- http://www.vishay.com/capacitors/ceramic/high-voltage/
- http://www.kemet.com/High-Volt-MLCC
- http://www.calramic.com/CalRamic-capacitors-products.html

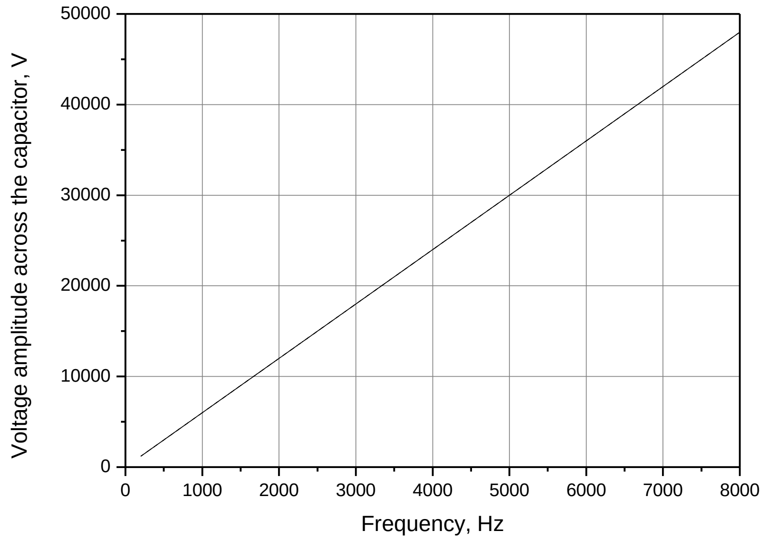


Fig. 13. The voltage amplitude V_C across the capacitor (voltage rate) calculated for $V_0 = 25$ V and the Helmholtz coil parameters $L = 320$ mH and $R = 8.38$ Ω.

The maximum capacitance of a high voltage capacitor with acceptable dimensions (not too large) we were able to find is 45 nF. This capacitor has the voltage rate just 3 kV. Therefore, V_0 must be further reduced, at least three times less, if we want to measure BH-loops within 1-2 kHz (see Fig. 13). As a result, the scanning field amplitude will be also reduced.

In Fig. 14, we show the performance of the large Helmholtz coil for $V_0 = 9$ V and the pickup coils having the following parameters:

- Internal coil diameter – 10 mm
- Length – 30 mm
- Wire diameter together with the enamel coating – 0.109788 mm (copper wire AWG-38)
- Number of layers – 6
- Turns in each layer – 273
- Total number or turns – 1638
- Total diameter (6 layers) – 11 mm

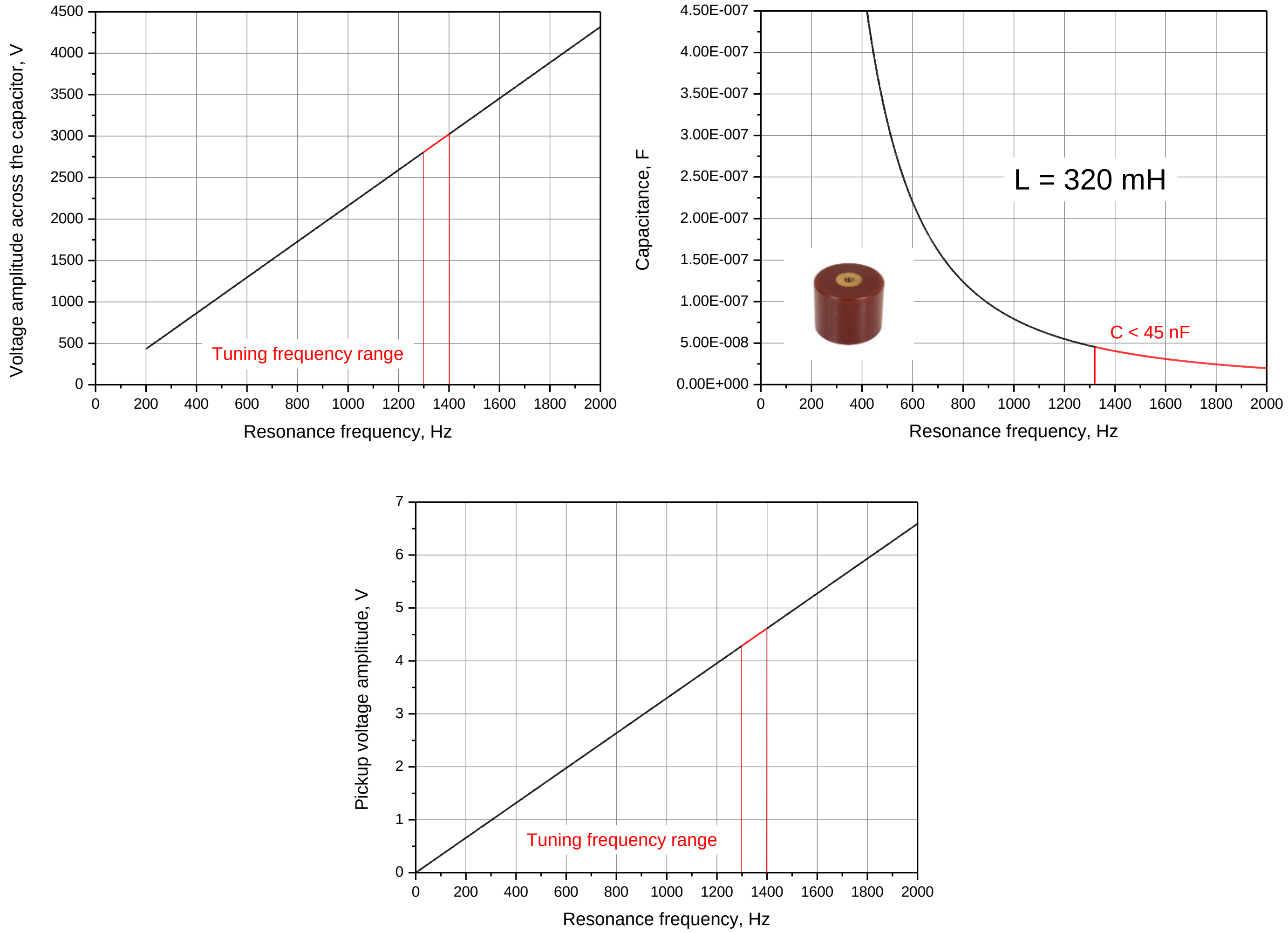


Fig. 14. Performance of the large Helmholtz coil and the pickup coils intended to work at the resonance frequency 1350 Hz.

The amplitude of the scanning magnetic field will be around 39 Oe: $H[\mathrm{Oe}] = \beta[\mathrm{Oe}\times\mathrm{A}^{-1}]V_0 / R$ with $\beta = 35.95$ Oe/A, $V_0 = 9$ V, and $R = 8.38$ Ω. Increasing the resonance frequency and decreasing the capacitance (< 45 nF), we can gradually increase the scanning field amplitude because the voltage rate of the capacitor will also increase. The pickup coils for this design are already manufactured. So, right now we can measure BH-loops at 1350 Hz. Starting from a sufficiently high frequency, it would be reasonable to use again the small Helmholtz coil which has smaller inductance resulting in a reduce voltage rate required for the compensating capacitor. Calculations for the small Helmholtz coil will be performed when a concrete project arises where high-frequency hysteresis loops are required.

When designing a high frequency excitation circuit, we recommend placing the compensating capacitor into a perforated case to eliminate shrapnel wounds in the event of its overheating and explosion.