Exercise 7.

Four Terminal Electronic Component

Required knowledge

- Calculation of inductance of toroidal and solenoidal inductors.
- Knowledge of basic definitions related to magnetism and magnetic materials, e.g., magnetic field strength (*H*), magnetic flux density (*B*), permeability, *B*-*H* curve, hysteresis loop, saturation, core loss, copper loss, inductance factor.
- Interpretation of quantities at the end of this guide, and interpretation of any of the quantities that are mentioned in the laboratory exercises.
- Connection between the current and induced voltage in an inductor. Calculation of *H* and *B* in an inductor. Calculation for sinusoidal excitation.
- Kinds of losses in a transformer/inductor, e.g., copper loss, core loss (hysteresis loss, eddy current loss). Why laminated cores are used? How the skin effect changes the copper loss?
- In circuit measurement.
- Parameters and models (equivalent circuit) of transformers, e.g., how core and copper losses, leakage/magnetizing reactances are modeled, dependency between turn ratio and secondary/primary voltage and current. Insertion loss.

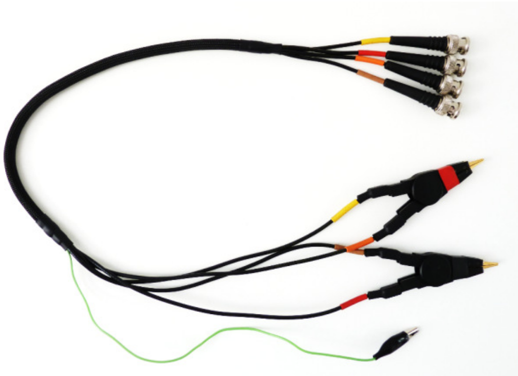
Aim of the measurement

You will learn how to model impedances and four terminal electrical components. The measurement is primarily connected to test of materials, parameter identification and in-circuit measurements.

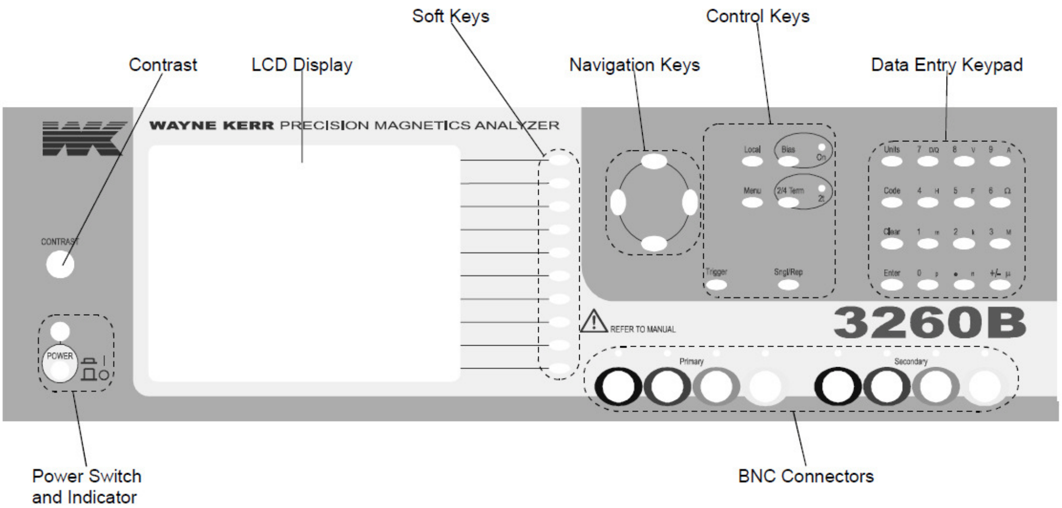
Measurement instruments

Precision Magnetics Analyzer
Wayne Kerr 3260B

Kelvin Clip Leads



The Front Panel

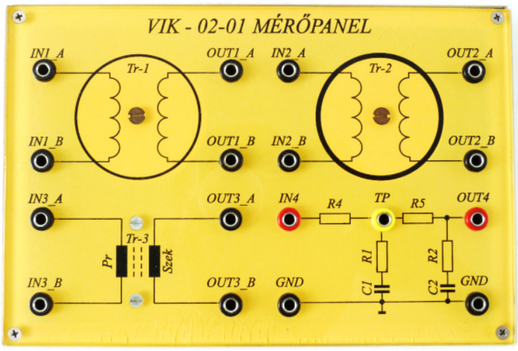


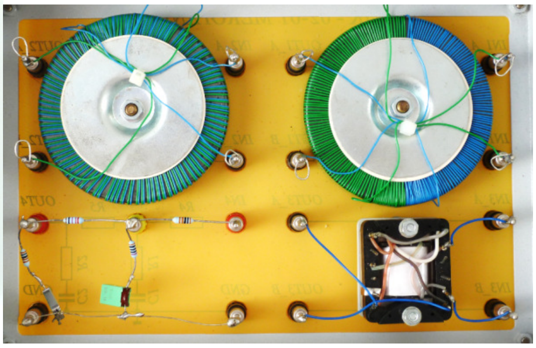
Main features of the Magnetics Analyzer:

- Frequency range: 20 Hz – 3 MHz
- Drive Level: 1 mV to 10 V_{rms} into open circuit,
  5 µA to 200 mA_{rms} into short circuit
- Source Impedance: 50 Ω

Test board

loose coupling tight coupling tight coupling loose coupling



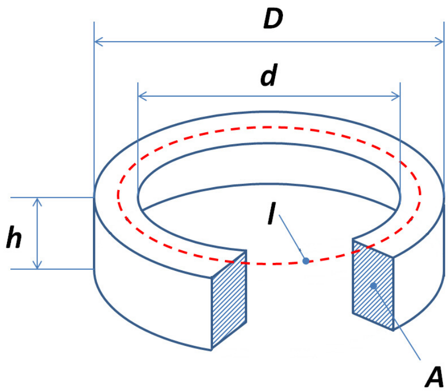


Ferromagnetic parameter of the DUT

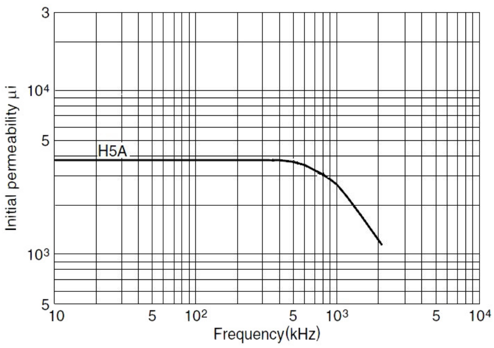
- Type: TDK H5A
- Core material: ferrite
- Core form: toroid
- Recommended maximum frequency: 0,2 MHz
- Initial permeability, μ_i : 3300 -0….+40%
- Max. flux density , B_m: 410 mT @ H=1194 A/m
- Inductivity factor, A_L: 4300±25% nH

  Core size:

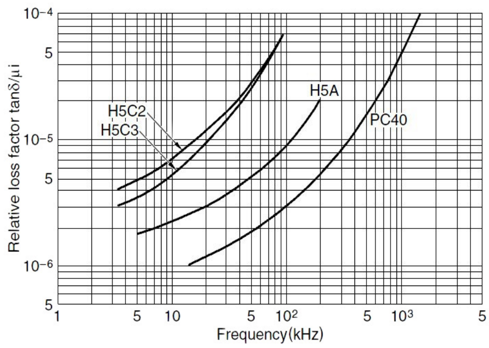
  D = 68 mm, d = 44 mm, h = 13,5 mm



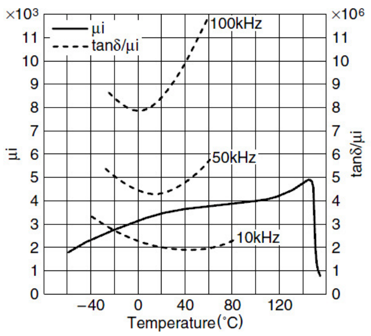
INITIAL PERMEABILITY, µi vs. FREQUENCY CHARACTERISTICS
Mn-Zn FERRITE



RELATIVE LOSS FACTOR, tanδ/ µi vs. FREQUENCY CHARACTERISTICS
Mn-Zn FERRITE



INITIAL PERMEABILITY, µi, RELATIVE LOSS FACTOR, tanδ/µi vs. TEMPERATURE CHARACTERISTICS
H5A



- Number of primary turns, N_p: 110
- Number of secondary turns, N_s: 110
- Cross section of the copper wire, A_{CU}: 0,05 mm^2
- Specific resistance of the copper: 1,678*10^{-8} Ωm
- Diameter of isolated wire d_w: 0,6 mm
- Coupling: loose coupling (Tr-1), tight coupling (Tr-2)

Required knowledge (repetition)

Classifications of Magnetic Materials

When a material is placed within a magnetic field, that shows magnetic properties, but sometimes the reaction is too weak to notice. Usually the people refer to it as nonmagnetic material. In fact this is a kind of magnetic behavior, and all matter have magnetic properties. You can classify the materials their magnetic properties into the following five major group: *diamagnetic, paramagnetic, ferromagnetic, ferrimagnetic, antiferromagnetic*. The origin of magnetism can be explained by the atomic and molecular structure of the material, the orbital and spin motions of electrons.

Relation between magnetic field strength and magnetic flux density is:

$$B = \mu_0 \cdot \mu_r \cdot H = \mu_0 \cdot (1 + \chi) \cdot H,$$

where B is the magnetic flux density, $\left[\frac{Vs}{m^2}\right]$, $[T]$

μ_0 is the vacuum permeability, $\mu_0 = 4\pi \cdot 10^{-7} \frac{Vs}{Am}$

μ_r is the relative permeability, $[-]$

H is the magnetic field strength, $\left[\frac{A}{m}\right]$

χ is the magnetic susceptibility, $[-]$

Note: The magnetic properties of the materials have temperature dependence, but next paragraph doesn't talk about it.

Diamagnetic: In these materials the atoms haven't magnetic moment, and the B flux density is lower than outside of them. The magnetic susceptibility is small and negative, typically around -10^{-5}. Diamagnetic materials are the noble gases, bismuth, mercury, silver, copper, water, sulfur, organic materials, type 1 superconductors etc.

Material	χ (x 10^{-5})
Bismuth	-16.6
Mercury	-2.9
Silver	-2.6
Copper	-1.0
Water	-0.9

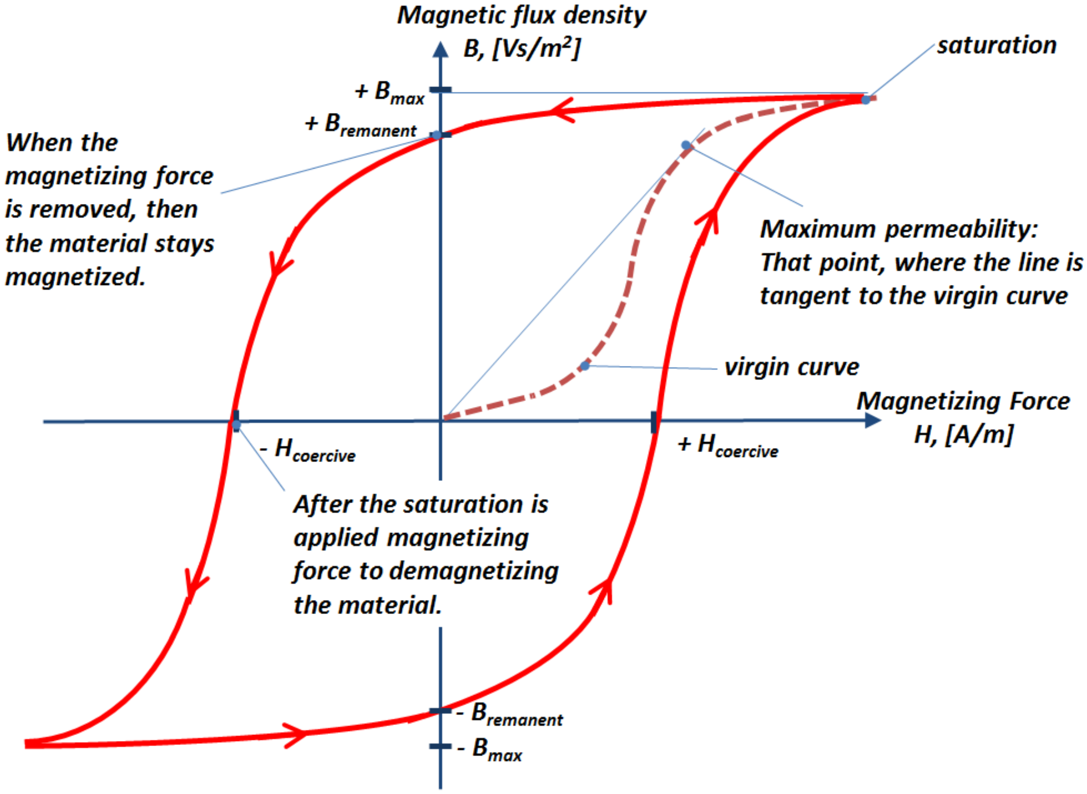
Paramagnetic: In these materials the atoms have randomly oriented magnetic moments, and the B flux density is a bit higher than outside of them (for example iron oxide (FeO), uranium, platinum, tungsten, aluminum, lithium, magnesium, sodium, oxygen). The magnetic susceptibility is small (around 10^{-5}) and positive.

Material	χ (x 10^{-5})
Iron oxide	720
Uranium	40
Platinum	26
Tungsten	6.8
Aluminum	2.2

Ferromagnetic: In these materials the atoms are arranged into domains, and the domains have parallel aligned magnetic moments. The B flux density is much higher ($10^1 \ldots 10^6$) than outside of them, and it depends on the applied H magnetic field strength (hysteresis loop), the domain size and domain structure.

The ferromagnetic materials can be grouped into three subgroup:

1. Ferromagnetic base metals: iron, nickel cobalt.
2. Ferromagnetic alloys:
   a. It contains ferromagnetic base metals
   b. Heusler alloy: It doesn't contain ferromagnetic base metals
3. Ferrite: ferromagnetic base metals (or its oxide) + oxide of the other metals.



There are five different regions on the virgin (and the hysteresis) curve:

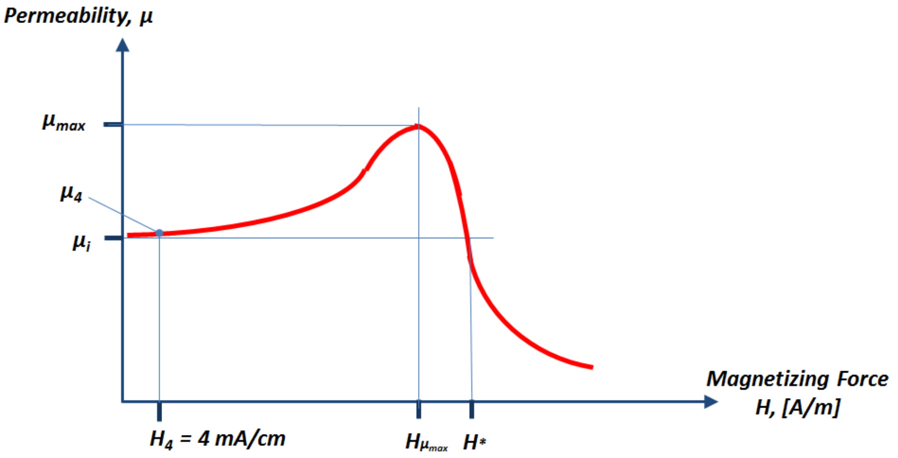
Note: there aren't sharp borders between these regions

1. Linear (or initial) region: $B = \mu_0 \cdot \mu_i \cdot H$
2. Square (or Rayleigh) region: $B = \mu_0 \cdot (\mu_i \cdot H + \upsilon \cdot H^2)$, υ = Rayleigh hysteresis constant
3. Maximum permeability region: $\mu_{diff} = \frac{1}{\mu_0} \cdot \frac{dB}{dH}$
4. Saturation region: see the figure
5. Paramagnetic region: $\chi_{diff} = \frac{dM}{dH} \approx 0.01$

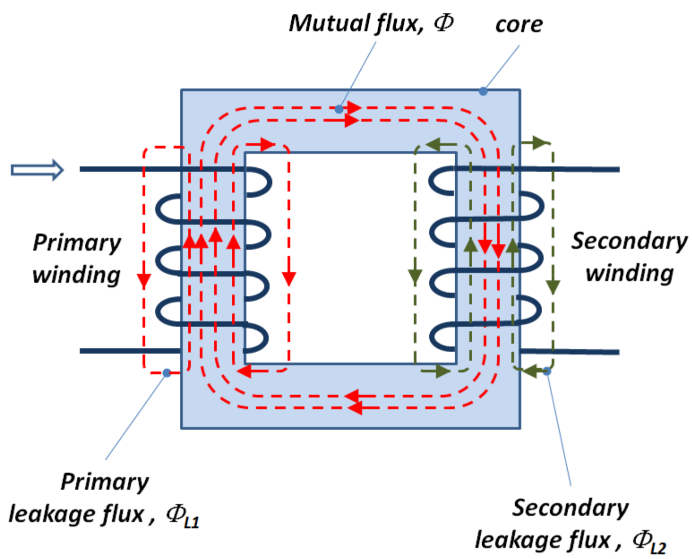
The measuring of the initial permeability is difficult.

$$\mu_i = \frac{1}{\mu_0} \cdot \lim_{H \to 0} \frac{B}{H}$$

Some materials at weak ($H \to 0$) magnetizing force can behave as paramagnetic way. In this case the domains can't sense the external force. It looks like the domains are "frozen in". That's why the initial permeability is measured at **4 mA/cm**. This value is enough big to "melt out" the domains, but it's enough small to the magnetizing force stays in the initial region.



Transformer:



Mutual flux: this flux is inside in the core (flux is closed through both windings).

Leakage flux: this flux is outside of the windings (flux is closed through only one windings, there is no coupling between windings).

The mutual inductance between two coils is:

$$M = \sqrt{L_1 \cdot L_2}$$

Quality factor (Q):

$$Q = \frac{\omega L_{series}}{R_{series}}$$

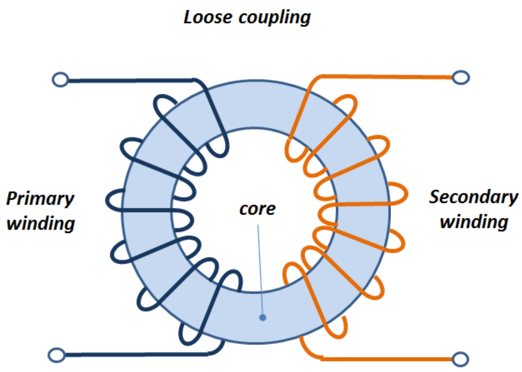
Coupling factor (*k*):

The definition of coupling factor is:

$$k = \frac{M}{\sqrt{L_1 \cdot L_2}}$$

Note: coupling between the two coils can never reach or exceed 1.

$k = 0$	no inductive coupling
$0 < k < 0.5$	loosely coupled
$k = 0.5$	☺
$0.5 < k < 1$	tightly coupled
$k = 1$	full or maximum inductive coupling

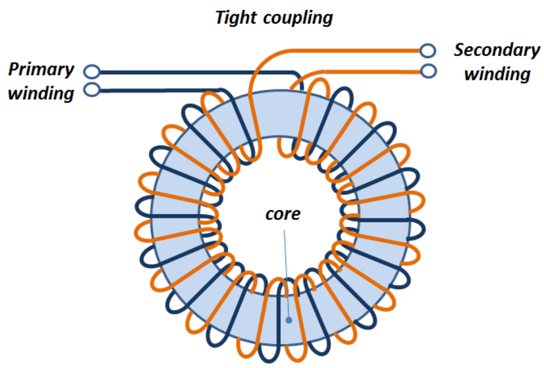


less parasitic capacitance

higher leakage inductance

higher dielectric strength

For example: High Voltage application



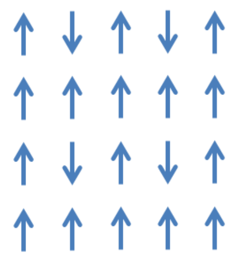
higher parasitic capacitance

less leakage inductance

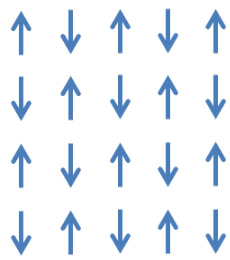
less dielectric strength

For example: telecommunication

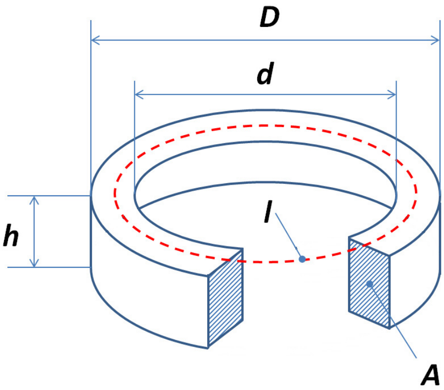
<u>Ferrimagnetic:</u> In these materials the atoms have mixed parallel and anti-parallel aligned magnetic moments. The magnetic susceptibility is large.



<u>Antiferromagnetic:</u> In these materials the atoms have anti-parallel aligned magnetic moments. The magnetic susceptibility is positive and small.



Calculation of inductance of toroidal inductor:



$$L = \mu_0 \cdot \mu_r \cdot \frac{A}{l} \cdot N^2$$

$$\mu_0 = 4\pi \cdot 10^{-7} \frac{Vs}{Am}$$

where,

- L = self-inductance of coil with core [H]
- μ_0 = permeability of vacuum
- μ_r = relative permeability
- A = cross-sectional area of toroidal core (mm^2)
- l = average length of magnetic path in the core [mm]
- N = number of turns

$$l = \frac{D+d}{2} \cdot \pi, \qquad A = \frac{D-d}{2} \cdot h$$

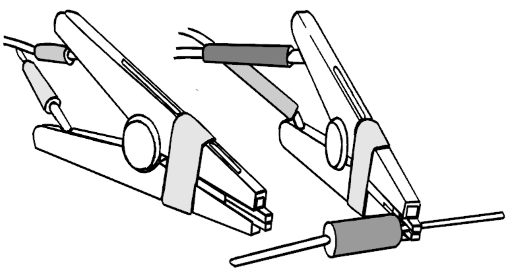
In the datasheet of torodial ferrite you can find the so called **inductance coefficient** A_l. It's defined as the self-inductance per unit turn of a coil of a given shape and dimensions wound on a magnetic core. A_l allows us to simply calculate the inductance by multiplying it with the square of the number of turns as the formulas on the right show.

$$A_l = \mu_0 \cdot \mu_r \cdot \frac{A}{l}, \qquad L = A_l \cdot N^2$$

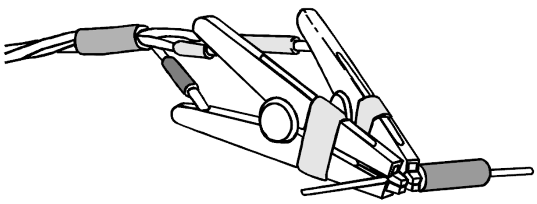
Measurement Tasks

1. Trimming

The purpose of trimming is to eliminate the effects of stray capacitance or series impedance in the connecting leads or fixture. For O/C (Open Circuit) Trim the Kelvin clips or fixture jaws should be separated by a distance equivalent to the DUT pin separation. For S/C (Short Circuit) Trim the connector jaws should be clipped to a piece of wire or a component lead as close together as possible. Do not connect the clips directly together: this does not provide the necessary 4-terminal short circuit and will lead to trim errors. The trimming requires some minutes.

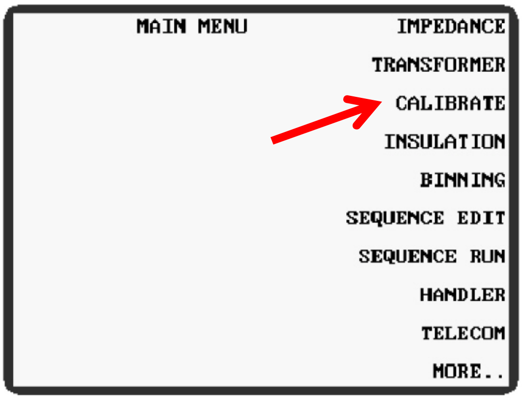


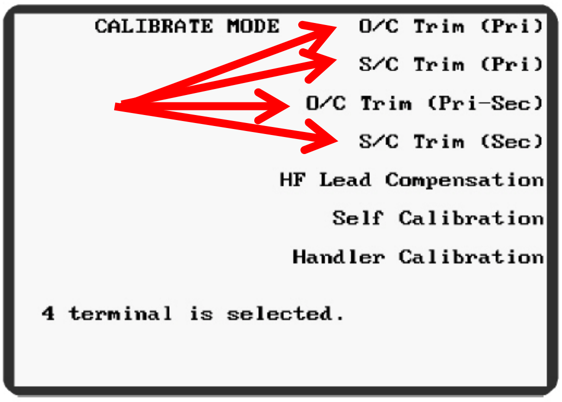
Connections for O/C trimming of Kelvin clips



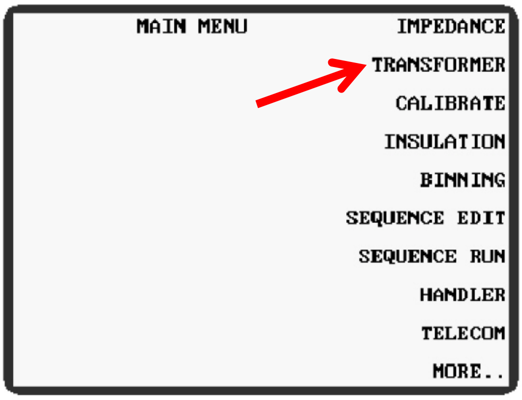
Connections for S/C trimming of Kelvin clips

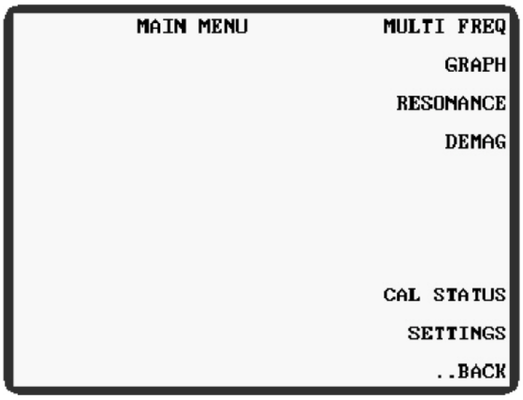
Carry out the trimming all frequencies!





After the trimming, checking is recommended.





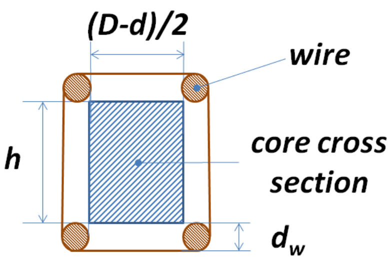
Use the *Main menu / Transformer mode /* R_{DC} *(Pri)* and R_{DC} *(Sec)* functions.

2. Calculation of the winding length and resistance

Calculate the length (l_w) and winding resistance (R) from number of turns, the core sizes, the specific resistance of the copper, and cross section of the wire! Don't forget it: there is a thin insulator on the wire! Measure the DC resistance of the inductors! Compare the measured values to the calculated value!

$$l_w = N\left(2\cdot\left(\left(\frac{d_w}{2}+\frac{D-d}{2}+\frac{d_w}{2}\right)+\left(\frac{d_w}{2}+h+\frac{d_w}{2}\right)\right)\right)$$

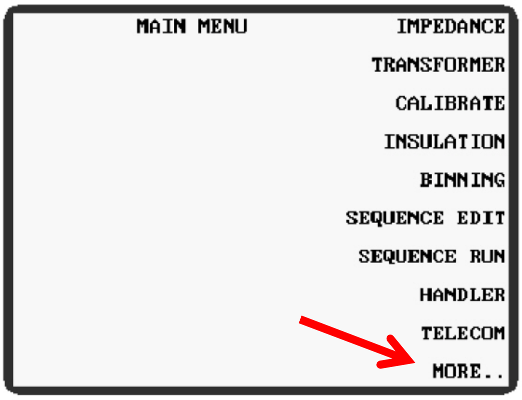
$$R = \rho\cdot\frac{l_w}{A_w}$$

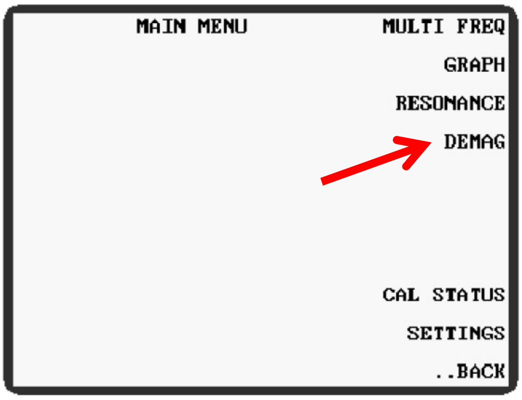


Use the *Main menu / Transformer mode /* R_{DC} *(Pri)* and R_{DC} *(Sec)* functions.

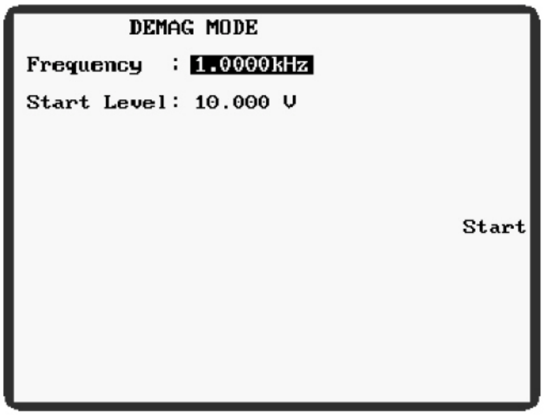
3. Demagnetization

Before the magnetic measurement, a demagnetization procedure is recommended. You can reach this ability of Analyzer on the second page in main menu.





Set up these parameters, and press the Start key.



Now, the ferrite core is demagnetized.

4. Initial permeability determination by impedance measurement

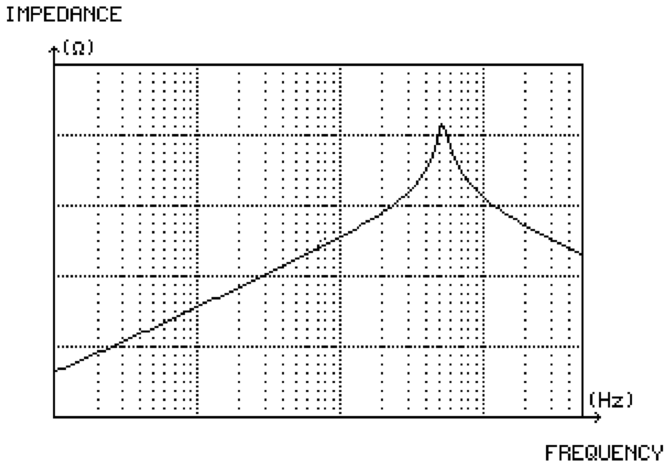
4.1. Measure the coil impedance at 1V in the range of 100 Hz…500 kHz!

Technical terminology: **coil = real inductor**

Set the next parameters in the proper menu:

Main menu / Impedance: Drive current 1mA$_{AC}$, ALC function OFF, speed Medium

Main menu / next / graph mode: Log (Hz), Log(Z)



All coils have some small real resistance, and parasitic capacitance exists between turns of the coil.

4.2. Measure the resonance frequency and the self-capacitance of the coil!

Try out the cursors, peak search function to find the resonant frequency. Use the resonance finding function of the analyzer. *Main menu / Resonance mode/ Find parallel.*

4.3. What is the max. measurement frequency if the systematic error caused by the resonance is not higher than 1%?

4.4. Measure the coil impedance at 150 Hz in the range of 1 mV…10 V using the Graph-mode of the Analyzer!

The next equation can work well in the case of small magnetizing force ($H \rightarrow 0$).

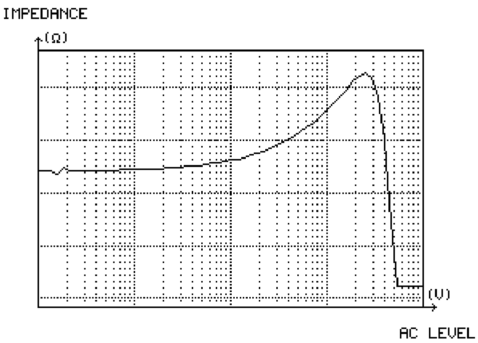
$$B = \mu_0 \cdot \mu_r \cdot H, \qquad \mu_r = \mu_i$$

See the hysteresis curve: if there is no magnetic field, there is no magnetization and you begin at the origin. (You have done the demagnetization.) If you increase the magnetizing force the permeability will change. It is shown in the figure on page 4 by dashed curve. The first magnetization curve is the virgin curve.

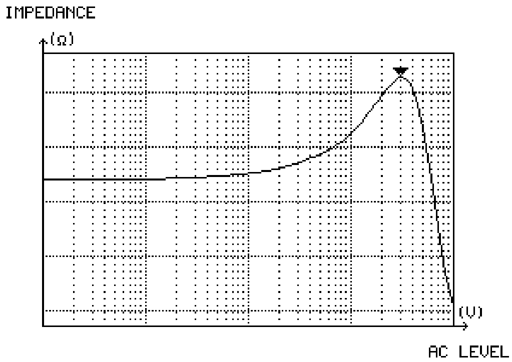
There is non-linear relation between B and H, μ_r depends on H.

You can see this effect on the impedance vs. low frequency AC level diagram.

Set the proper parameters in Impedance and Graph menu.



ALC function is ON



ALC function is OFF

4.5. Calculate $\mu_r(B_m)$ from the $Z(U)$ characteristics!

When you apply low frequency at the measurement, you can ignore the effect of parasitic capacitance. If you reorder the next equations, you are able to calculate the relative permittivity:

$$L = \mu_0 \cdot \mu_r \cdot \frac{A}{l} \cdot N^2 \, , \ |Z| = \omega \cdot L$$

Calculate μ_i and μ_{max} values, and compare them to datasheet values.

4.6. Measure the coil impedance at 150 Hz in the range of 50 µA…200 mA using the Graph-mode of the Analyzer!

Let's remember: the current is directly proportional to the magnetic field strength.

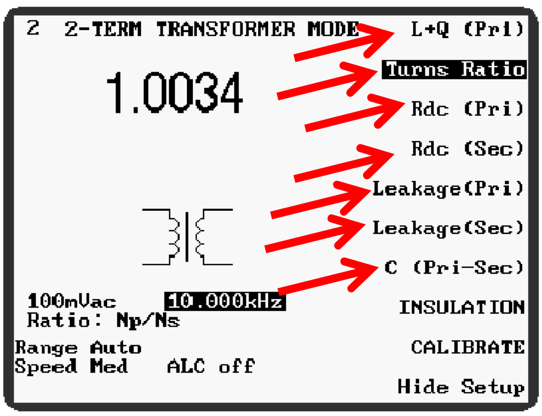
$$H = \frac{N \cdot I}{l}$$

Calculate the H^* value! H^* is given in $\mu(H)$ plot on page 5.

5. Transformer parameters measuring

5.1. Measure the model parameters at U_{eff} = 5V and f = 1 kHz! Measure the marked parameters! What are the differences between the two transformers? Compare them!

Use the *Main menu / Transformer mode*



6. In-circuit measurement on RC-network

Technical data of the RC-components:

$R_1 = 100\ \Omega \pm 0{,}1\%$
$R_2 = R_4 = 1\ \text{k}\Omega \pm 1\%$
$R_5 = 10\ \text{k}\Omega \pm 2\%$
$C_1 = 1\ \mu\text{F} \pm 5\%$
$C_2 = 100\ \text{nF} \pm 5\%$

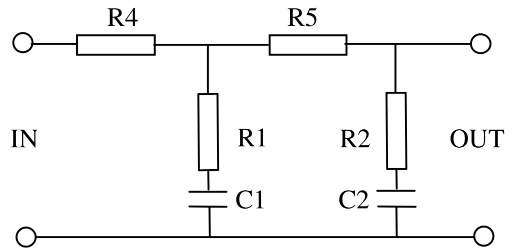


Figure 7–1. Schematic of low-pass filter to be measured

6.1. Measure all of the RC components using in-circuit technique! Are the measured values within the specified tolerance bands?

Some quantities related to magnetic materials

Notation	Name	Unit	Calculation
I, $\boldsymbol{I}$	Current, excitation current	A (mA)	
N	Number of turns	1	
Θ	Magnetic excitation	A (mA)	$\Theta = NI$
l	Average length of magnetic field	m (cm)	for a closed core.
H, $\boldsymbol{H}$	Strength of magnetic field	A/m (A/cm, mA/cm)	$H = \Theta/l = NI/l$ $\boldsymbol{H} = \mathrm{Re}\boldsymbol{H} + \mathrm{j}\mathrm{Im}\boldsymbol{H}$
H_m	Maximum strength of magnetic field	A/m (A/cm, mA/cm)	$H_m = \sqrt{2}\, H$ for sinusoidal H
B, $\boldsymbol{B}$	Magnetic flux density	T, Wb/m^2 (mT)	$B = \mu_0 \mu_r H$ $\boldsymbol{B} = \mu_0 \boldsymbol{\mu_r} \boldsymbol{H}$ $\boldsymbol{B} = \mathrm{Re}\boldsymbol{B} + \mathrm{j}\mathrm{Im}\boldsymbol{B}$
B_m	Maximum of magnetic flux density	T, Wb/m^2 (mT)	$B_m = \sqrt{2}\, B$ for sinusoidal B
μ	Absolute permeability	V·s/A·m	$\mu = B/H = \mu_0 \mu_r$
μ_0	Permeability of vacuum	V·s/A·m	$4\pi\cdot 10^{-7}$.
μ_r	Relative permeability	1	$\mu_r = \mu / \mu_0 = \mu_0^{-1} B/H$ can be a nonlinear function, i.e., $\mu_r = \mu_r(H)$
μ_a	Amplitude permeability	1	$\mu_a = \mu_0^{-1} B_m / H_m$ for variable excitation, H_{dc}=0.
$\boldsymbol{\mu}$	Relative complex permeability	1	$\boldsymbol{\mu} = \mu' - \mathrm{j}\,\mu''$ describes phase shift between B and H in non-ideal circumstances.
μ'	Real value of relative complex permeability	1	$\mu' = \mathrm{Re}\,\boldsymbol{\mu}$
$-\mu''$	Imaginary value of relative complex permeability	1	$-\mu'' = \mathrm{Im}\,\boldsymbol{\mu}$
$\lvert\boldsymbol{\mu}\rvert$	Absolute value of relative complex permeability	1	$\lvert\boldsymbol{\mu}\rvert = \mathrm{sqrt}\,(\mu'^2 + \mu''^2)$
μ_i	Relative initial permeability	1	$\mu_i = \mu_a = \mu_0^{-1} B_m / H_m$ at limiting case B_m, $H_m \to 0$
μ_4	Initial permeability @ H_m= 4 mA/cm	1	$\mu_4 = \mu_a = \mu_0^{-1} B_m / H_m$ measured at H_m= 4 mA/cm by definition
μ_{max}	Relative maximal permeability	1	peak value of curves $\mu_r(H)$ or $\mu_r(B)$
μ_e	Relative effective permeability	1	kind of equivalent permeability of a core that has, e.g, irregular shape, mixed material, air gap or any non-ideal properties.
A	Cross section area of core	m^2 (cm^2)	Note: it can be less than the physical cross-section, e.g., laminated core
Φ	Magnetic flux	Wb, V·s	$\Phi = BA$
L	Inductivity	H, Wb/A	$L = N\Phi / I$ $L = \mu_0 \mu_r N^2 A/l = 10^{-9} N^2 A_L$
A_L	Inductance factor, A_L	nH	$A_L = 10^9 \mu_0 \mu_r A/l$ (inductivity can be calculated as $L = 10^{-9} N^2 A_L$, see above)
Z_s	Serial impedance of an inductance	Ω, V/A	$\boldsymbol{Z_s} = R_s + \mathrm{j}\omega L_s = \mathrm{j}\omega\, \mu_0 (\mu' - \mathrm{j}\,\mu'') N^2 A/l$, $L_s = \mu_0 \mu' N^2 A/l$ $R_s = \omega\, \mu_0 \mu'' N^2 A/l$ $\lvert\boldsymbol{Z_s}\rvert = \mathrm{sqrt}\,(R_s^2 + \omega^2 L_s^2) = \omega\, \mu_0 \lvert\boldsymbol{\mu}\rvert N^2 A/l$
Q	Quality factor	1	$Q = \omega L_s / R_s = \mu'/\mu''$
tgδ	Tangent of loss angle	1	$\mathrm{tg}\delta = 1/Q = \mu''/\mu'$
Z_s'	Corrigated serial impedance	Ω, V/A	$\boldsymbol{Z_s}' = R_v + \mathrm{j}\omega L_s = \mathrm{j}\omega\, \mu_0 (\mu' - \mathrm{j}\,\mu'') N^2 A/l$, $L_s = \mu_0 \mu' N^2 A/l$ $R_v = \omega\, \mu_0 \mu'' N^2 A/l$ $\lvert\boldsymbol{Z_s}'\rvert = \mathrm{sqrt}\,(R_v^2 + \omega^2 L_s^2) = \omega\, \mu_0 \lvert\boldsymbol{\mu}\rvert N^2 A/l$, $R_v = R_s - R_{Cu}$

Some quantities related to magnetic materials (cont.)

Notation	Name	Unit	Calculation
ρ	Electrical resistivity (also called specific electrical resistance)	Ωm, Ω mm^2/m	
R_{Cu}	Resistance for DC current	Ω, V/A	$R_{cu} = \rho\, l_{Cu} / A_{Cu}$
R_h	Hysteresis resistance	Ω, V/A	It models the hysteresis loss
$R_ö$	Eddy current resistance	Ω, V/A	It models the loss caused by eddy current
R_v	Loss resistance	Ω, V/A	$R_v = R_h + R_ö = R_s - R_{Cu}$ It models the core loss.
R_s	Serial resistance	Ω, V/A	$R_s = R_{Cu} + R_h + R_ö = R_{Cu} + R_v$ Models the core and copper loss
P	Power loss	W (mW)	$P = I^2 R_s = I^2 (R_{Cu} + R_h + R_ö)$
P_{Cu}	Copper loss	W (mW)	$P_{Cu} = I^2 R_{Cu}$
P_h	Hysteresis loss	W (mW)	$P_h = I^2 R_h = c_1 B_m^p f$ $p = 1…3$
$P_ö$	Eddy current loss	W (mW)	$P_ö = I^2 R_ö = c_2 B_m^q f^2$ $q = 1…3$ for sinusoid B
P_v	Core loss	W (mW)	$P_v = I^2 R_v = P_h + P_ö = c_1 B_m^p f + c_2 B_m^q f^2$ for sinusoid B
P_v / f	Loss per period, B_m = constant	W/Hz (mW/Hz)	$P_v / f = c_1 B_m^p + c_2 B_m^q f$ B_m = constant!
m	Mass of core	kg (g)	
p_v	Specific core loss	W/kg (mW/g)	$p_v = P_v / m$
J	Current density	A/mm^2	$J = I/A_{Cu}$
δ	Skin depth	mm	$\delta = \mathrm{sqrt}\,(\rho/(\pi\, \mu_0\, \mu_r f))$