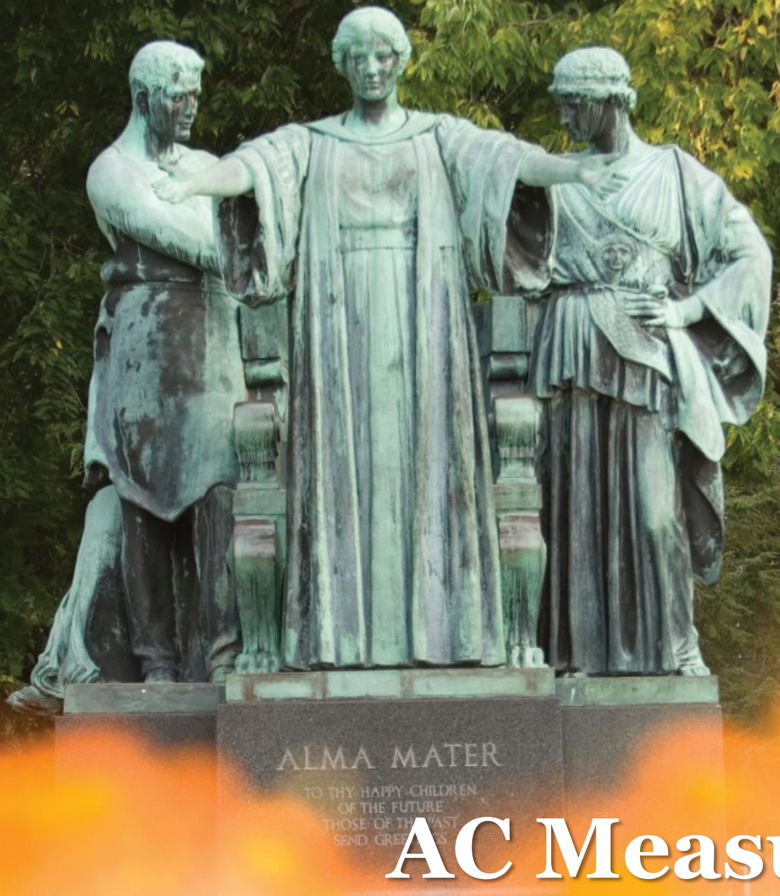


UNIVERSITY OF ILLINOIS
AT URBANA-CHAMPAIGN

AC Measurement of Magnetic Susceptibility

Physics 401, Fall 2019
Eugene V. Colla

Outline

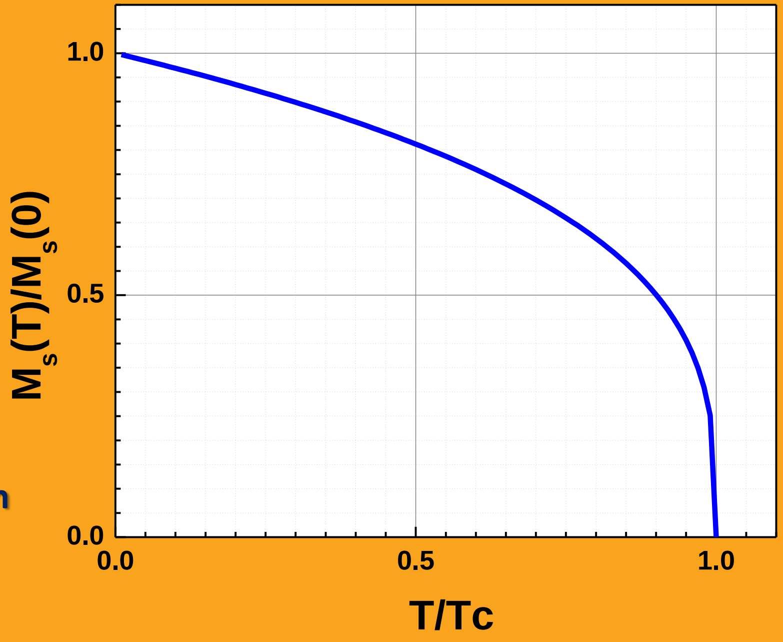
- **Ferromagnetism**
- **Measurement of the magnetic properties of the materials**
- **Lab experimental setup and experiments**
- **Some results**

Ferromagnetism. Definition.

Some materials below a certain temperature (Tc) give rise to the magnetic field in absence of an applied field.

This magnetization is called spontaneous, the phenomenon – ferromagnetism and materials exhibiting this feature – ferromagnetics.

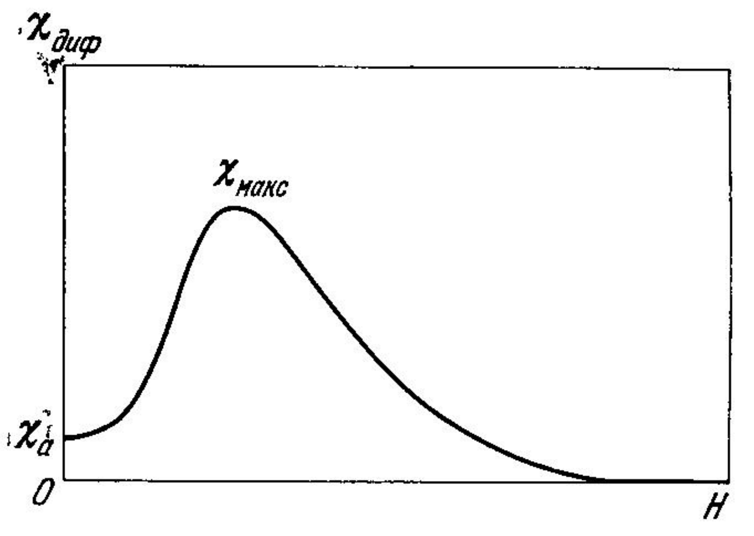
The main parameter of the ferromagnetic phase transition is spontaneous magnetization



Typical behavior of spontaneous magnetization as function of temperature

Ferromagnetic materials.

Aleksandr Stoletov
(1839 –1896)



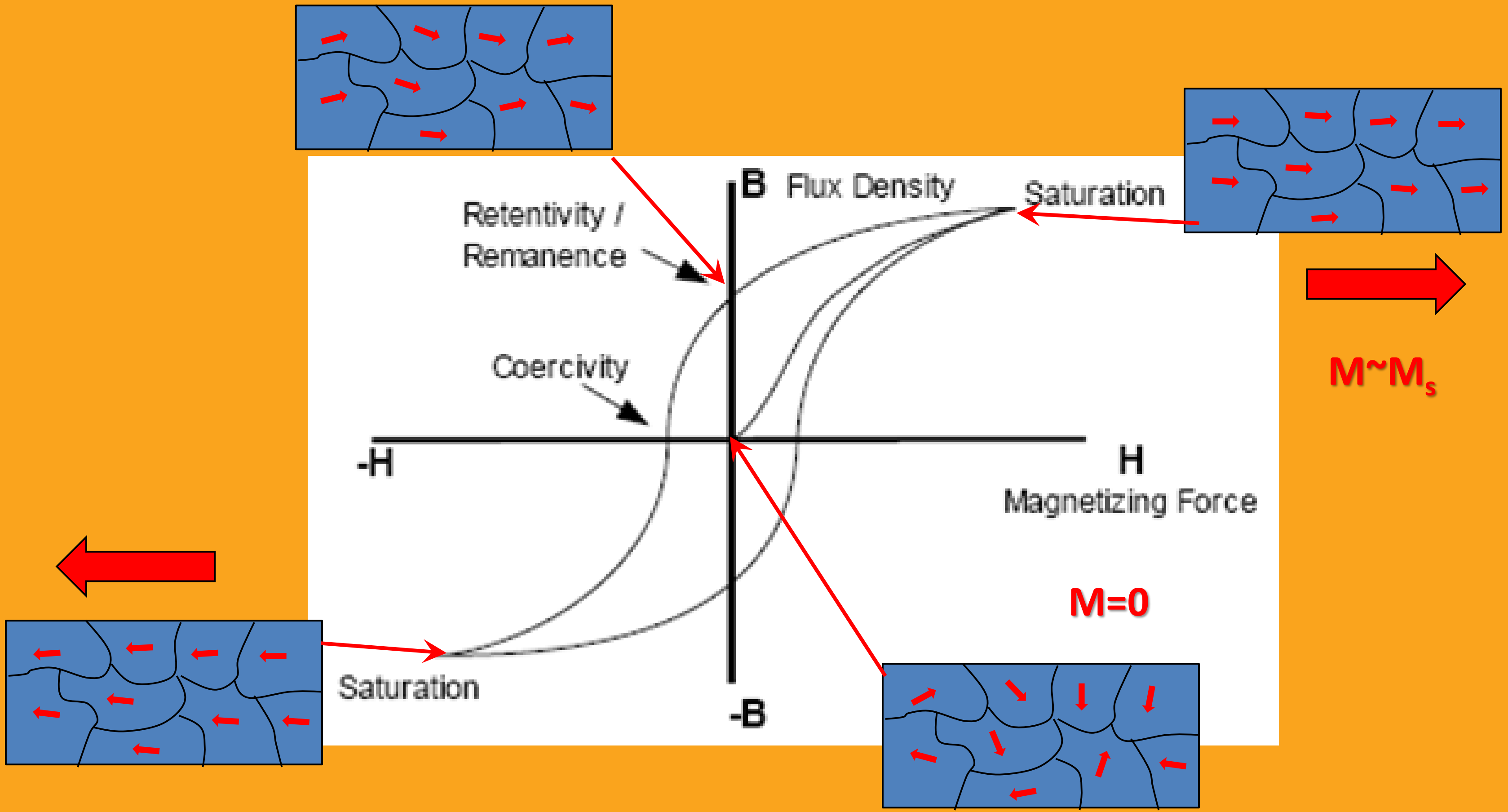
"Stoletov" curve

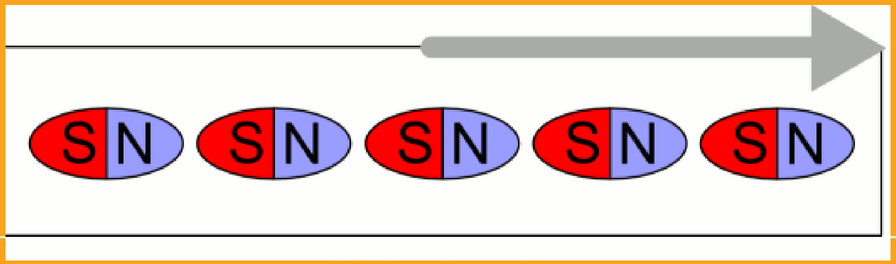
Material	Curie temp. (K)
Co	1388
Fe	1043
$Fe_2O_3^*$	948
$FeOFe_2O_3^*$	858
$NiOFe_2O_3^*$	858
$MgOFe_2O_3^*$	713
MnBi	630
Ni	627
MnSb	587
$MnOFe_2O_3^*$	573
$Y_3Fe_5O_{12}^*$	560
CrO_2	386
MnAs	318
Gd	292

$$\boxed{\chi = \frac{dM}{dH}}$$

Stoletov performed pioneer works in area of ferromagnetic materials but better known by his research in photoelectric effect.

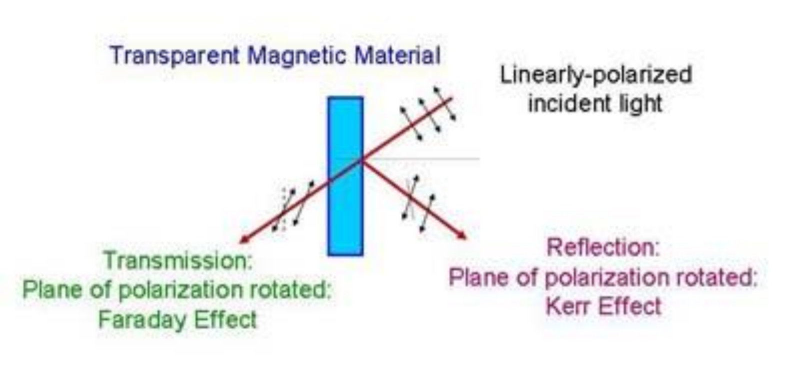
Domains. Hysteresis loop.



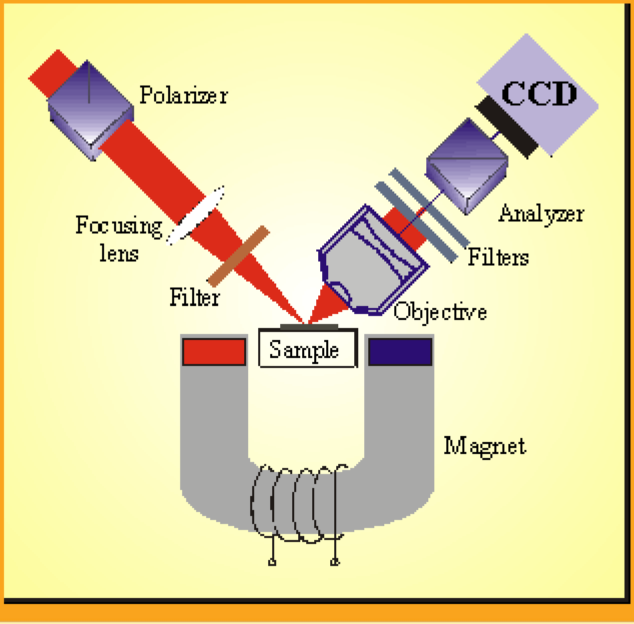


* Courtesy Wikipedia

Kerr Effect. Visualization of the Domains



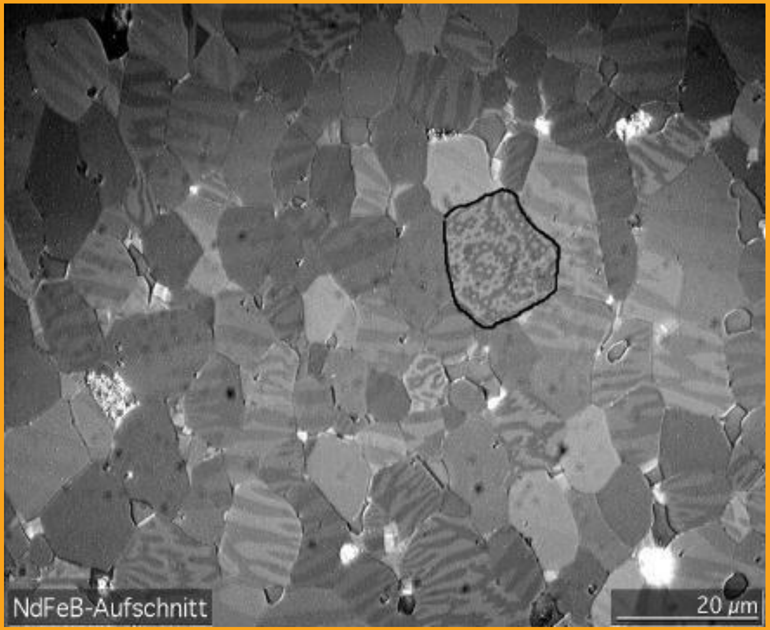
John Kerr
17 Dec 1824 –
15 Aug 1907



The Diagram of Typical Kerr Microscope

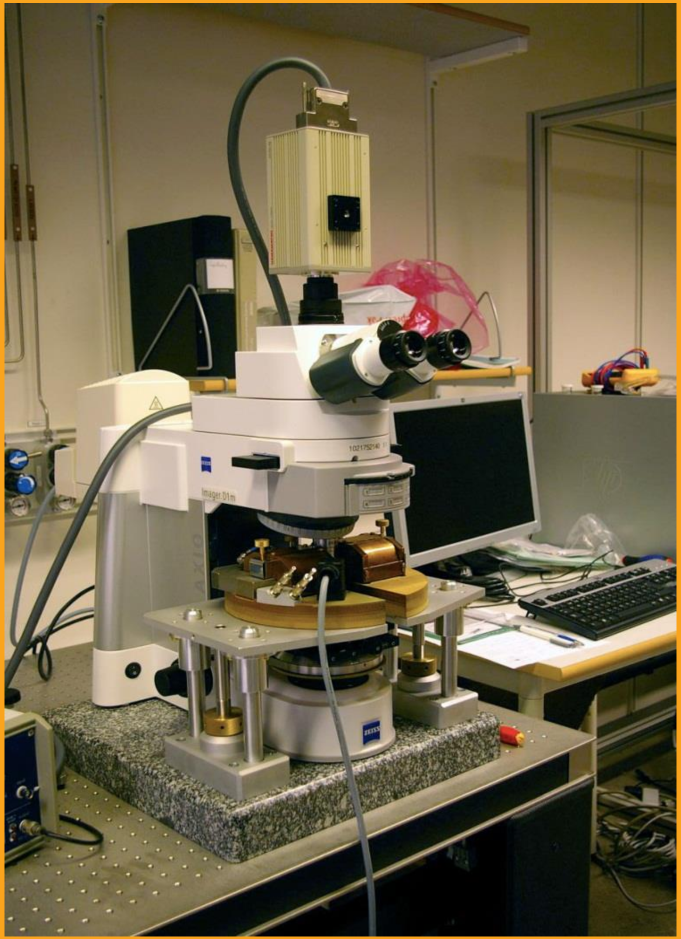
Courtesy of Radboud University, Nijmegen
The Netherlands

Domains



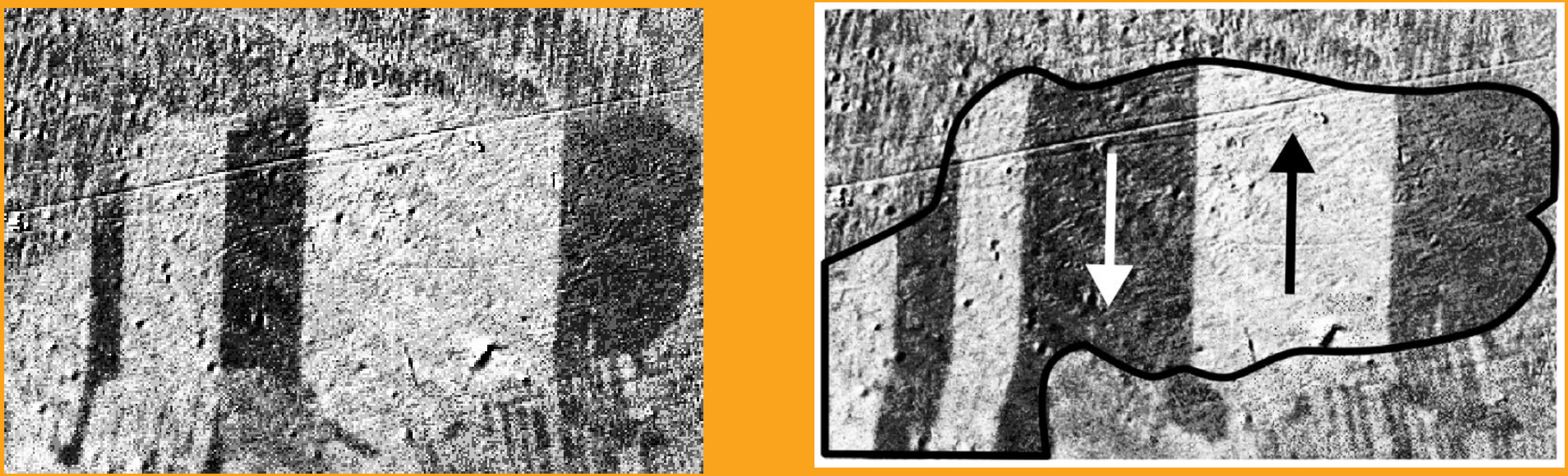
Several grains of NdFeB with magnetic domains made visible via contrast with a Kerr microscope.

Courtesy of Wikipedia



Kerr microscope
Courtesy of University of Uppsala (Sweden)

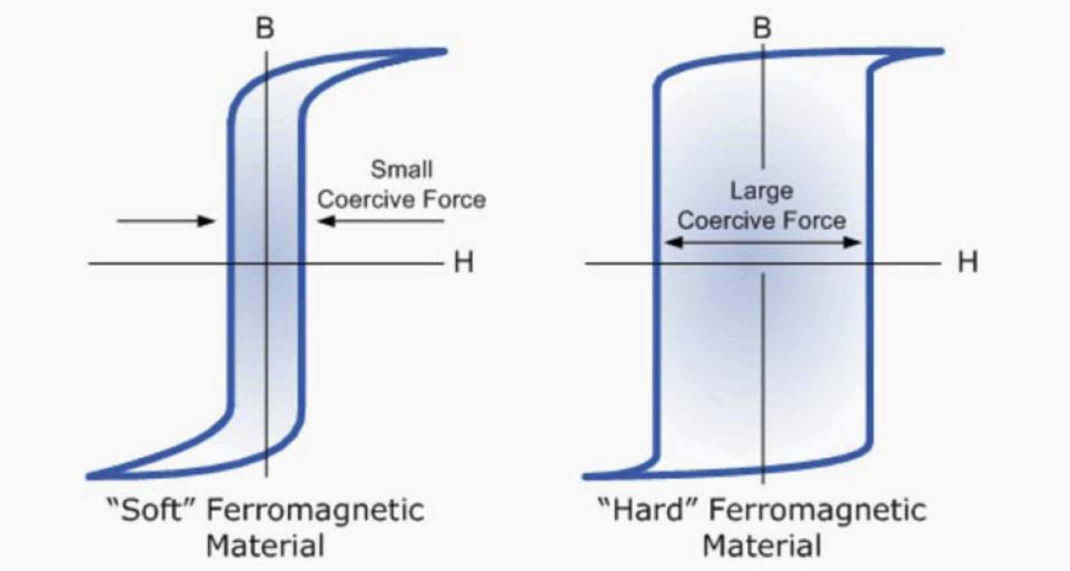
Domains



Moving domain walls in a grain of silicon steel caused by an increasing external magnetic field

Courtesy of Wikipedia

Hysteresis Loops. Remagnetization loses



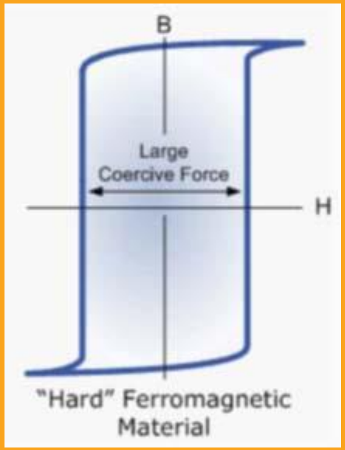
Energy of the magnetic field

$$W = V \int HdB$$

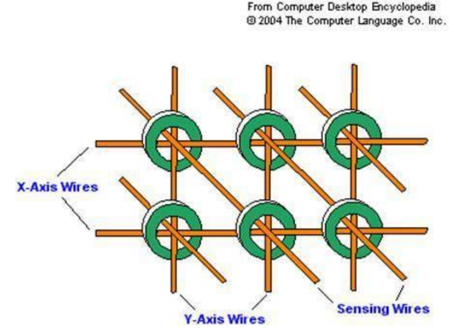
By cycling around the loop

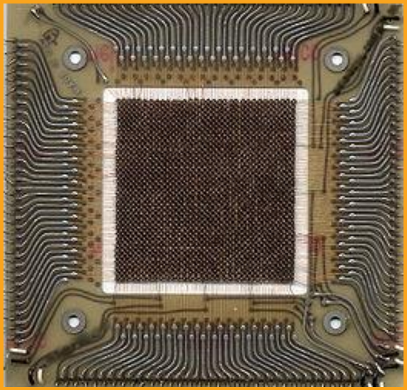
$$W_{loop} = V \oint HdB = V{*}Loop\_area$$

“Hard” materials. Application.



RAM memory

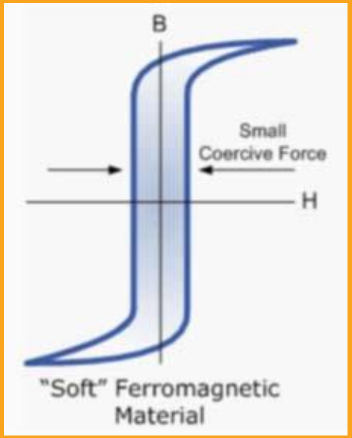




Permanent magnets

Hard drives, floppy, magnetic tape

“Soft” materials. Application.



Chokes, inductors

Power transformers

Magnetic Field, Susceptibility etc.

$$B = \mu_0 \left(H + M \right)$$

B – magnetic induction

M – magnetization, in general M(H)

$$M = \chi H$$

χ – magnetic susceptibility, in general χ(H)

$$B = \mu_0 \left(1 + \chi \right) H = \mu_0 \mu_r H = \mu H$$

$$\mu_r = 1 + \chi$$

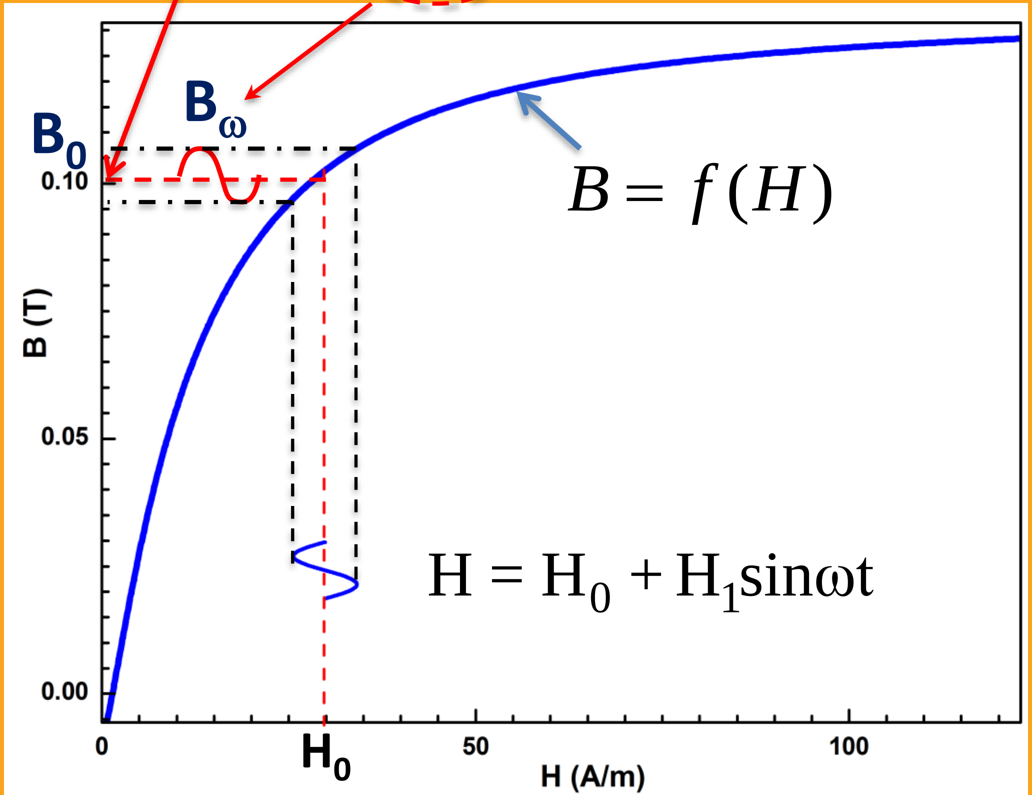
$$\mu = \mu_0 \mu_r = \frac{dB}{dH}; \quad \mu_r = \frac{1}{\mu_0} \frac{dB}{dH}$$

Modulation Spectroscopy

$B = f(H) \qquad H = H_0 + H_1 \sin\omega t$

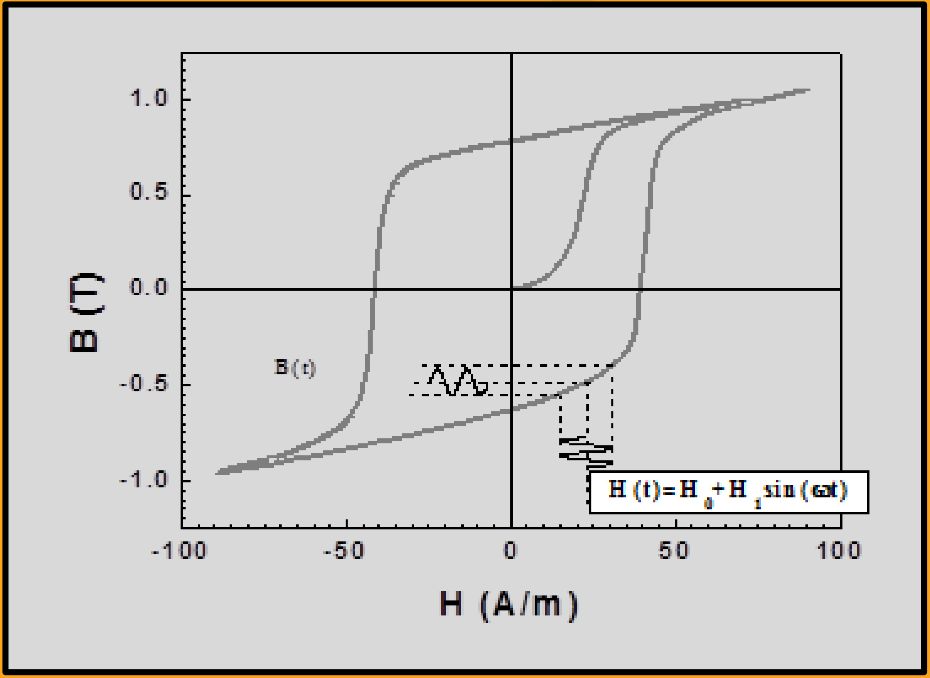
$$B = f(H_0) + \frac{df}{dH}(H_1 \sin\omega t) + \ldots$$

H_1=const



$$B_\omega \sim \frac{dB}{dH}$$

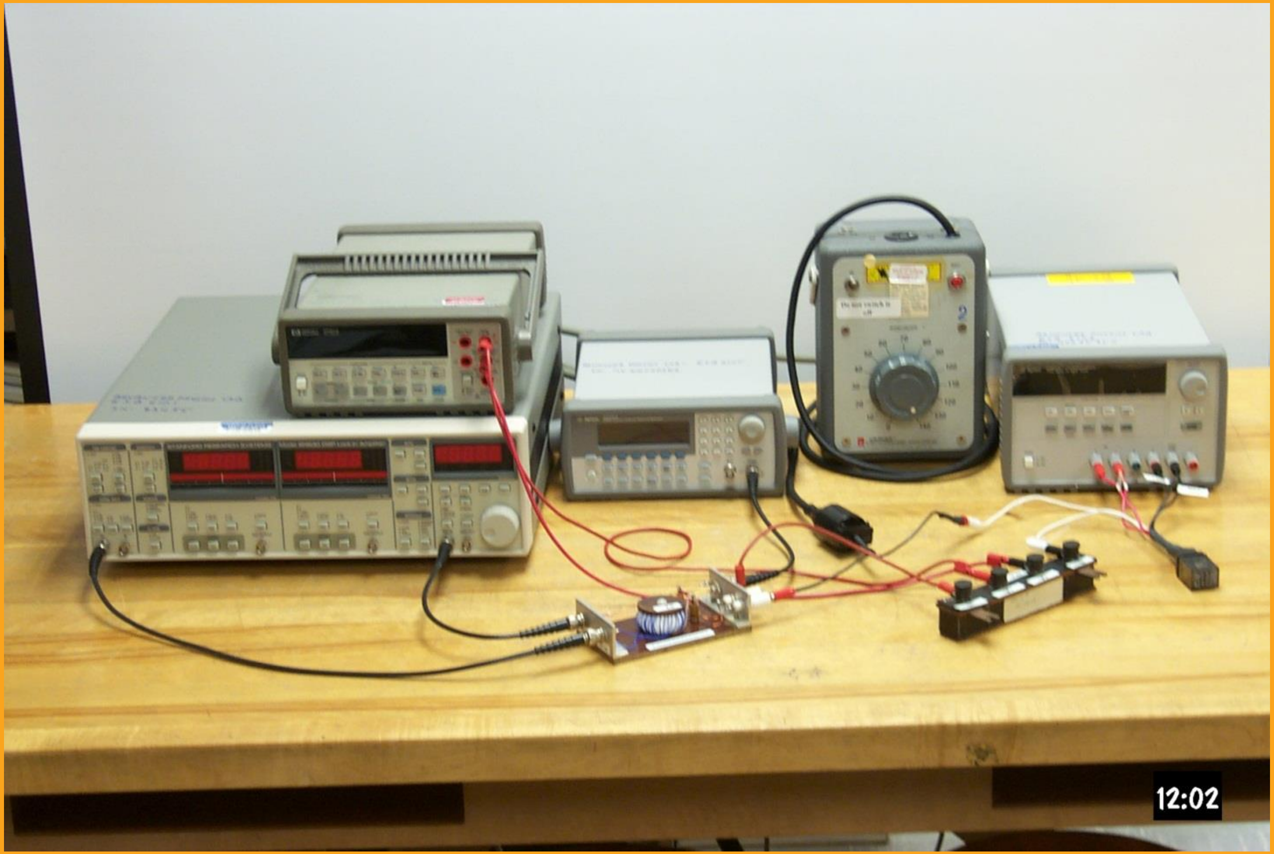
Measuring the magnetic permeability



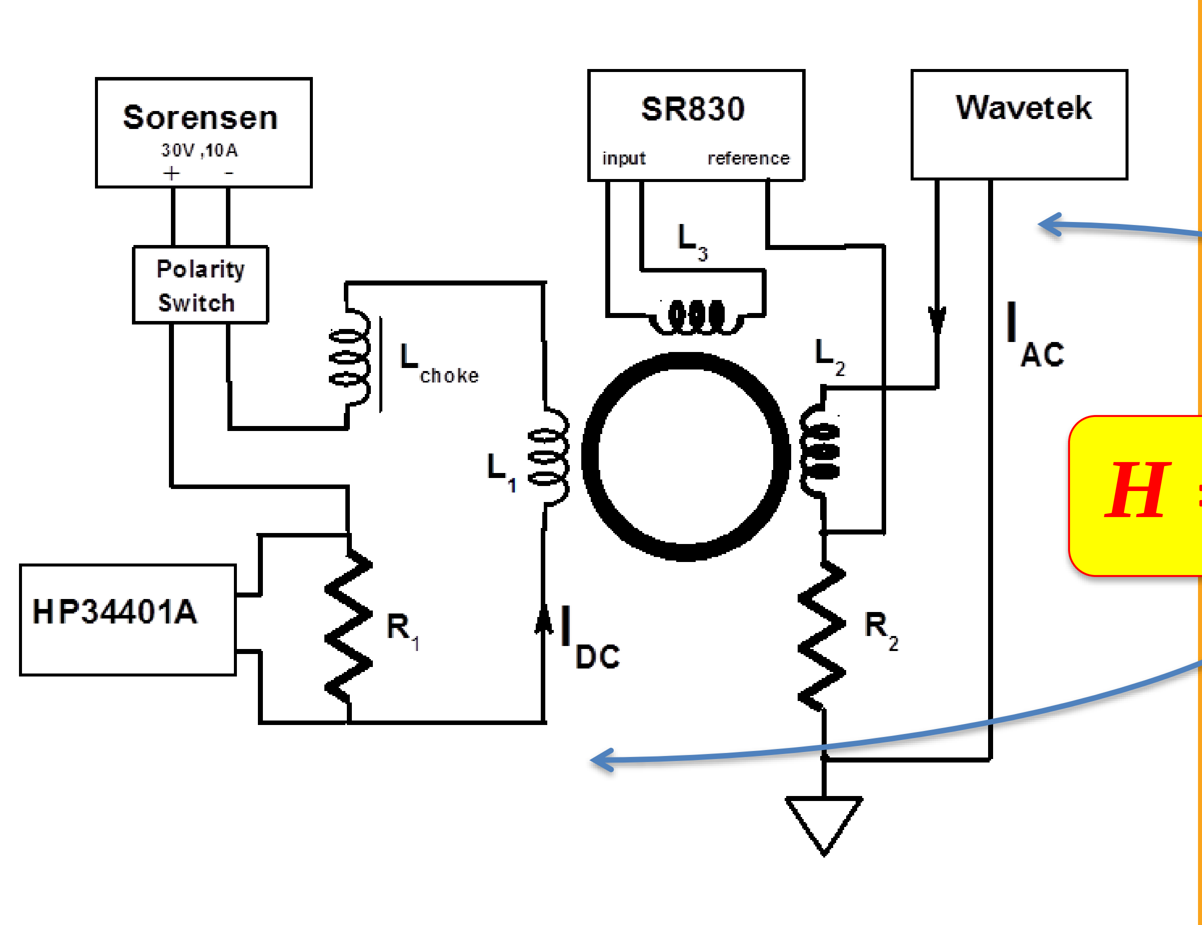
By applying a small modulation of the H field we can measure the derivative of the B-H hysteresis loop or dependence of the magnetic permeability on H field

$$\mu(H_0,\omega)=\mu_0(1+\chi(H_0,\omega))=\left.\frac{dB}{dH}\right|_{H_0,\omega}$$

Setup #1. Investigation of the hysteresis loops.



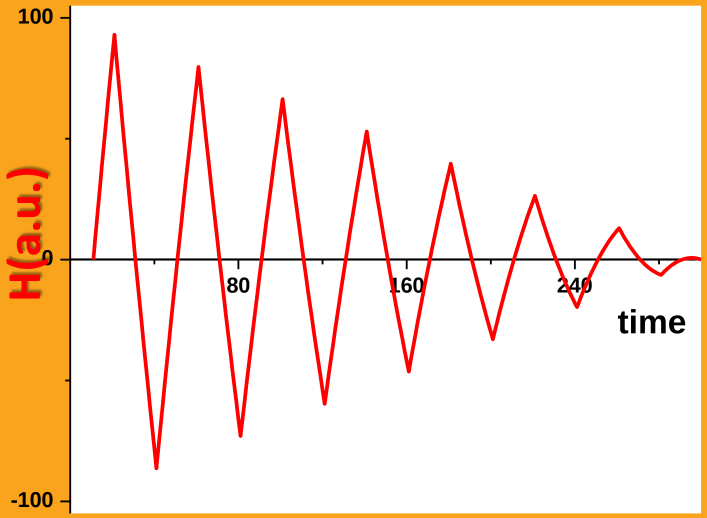
Setup #1. Investigation of the hysteresis loops.



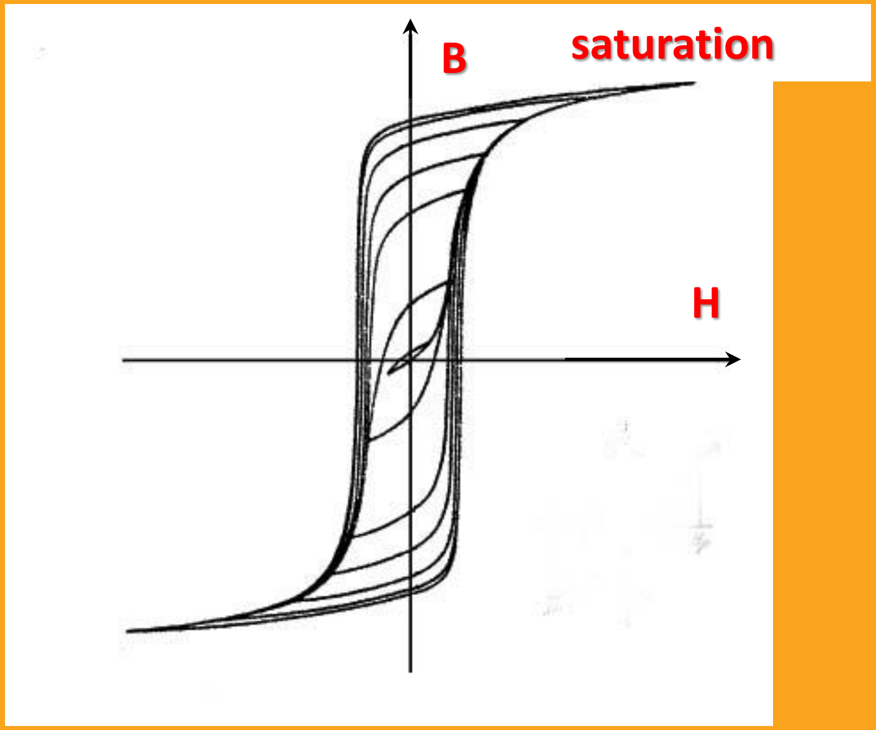
$$H = \frac{N_p I_p}{2\pi r}$$

$$H = H_0 + H_1 \cos \omega t$$

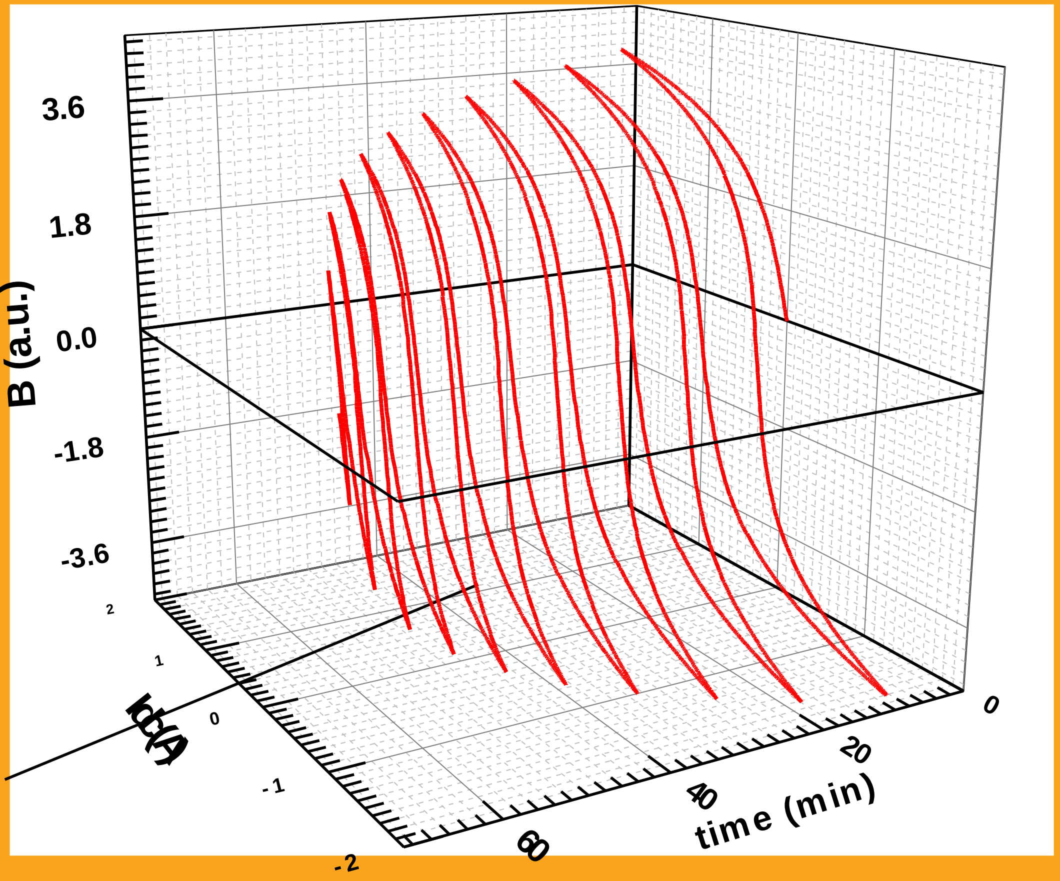
Major/minor loops. Demagnetization



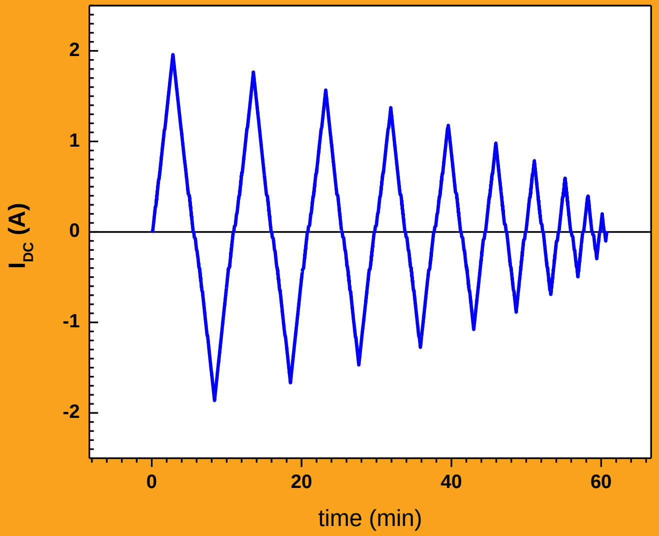
Waveform of H-field



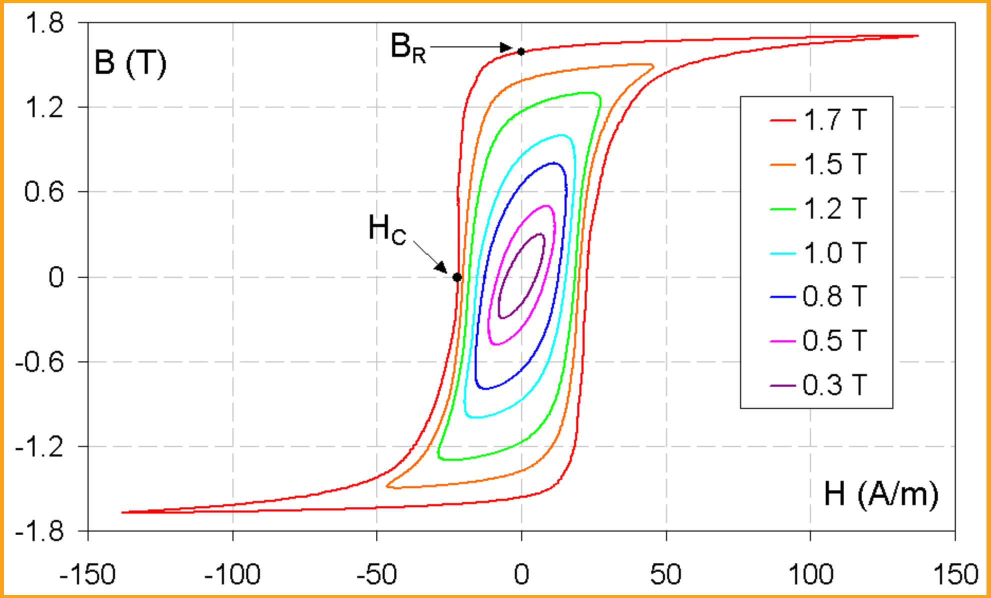
Demagnetization



Demagnetization of 4C65 toroid from Ferroxcube



Hysteresis Loops



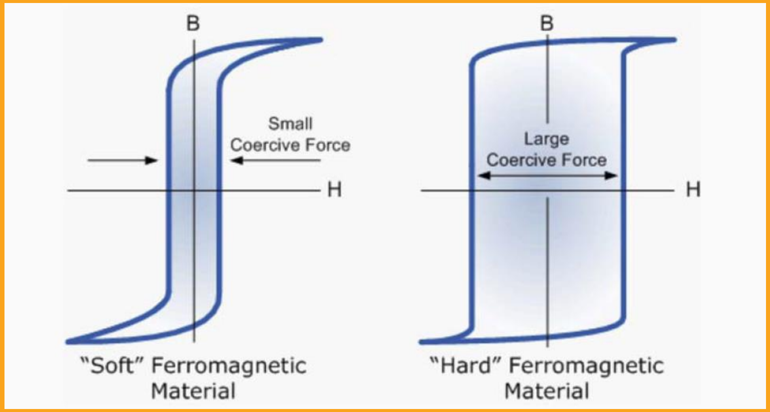
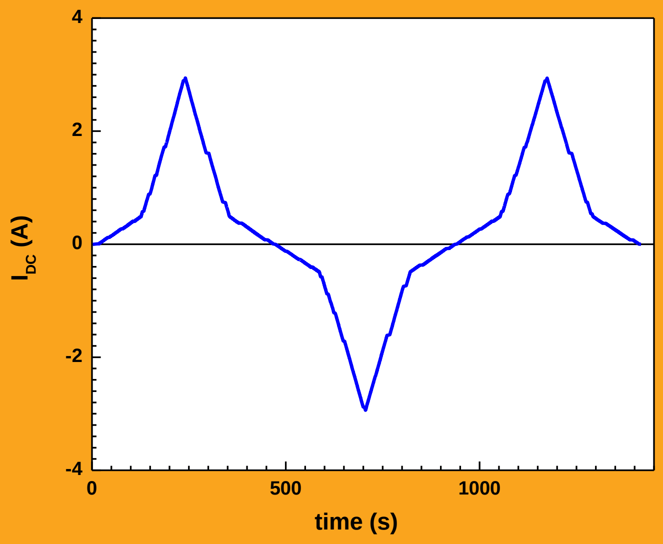
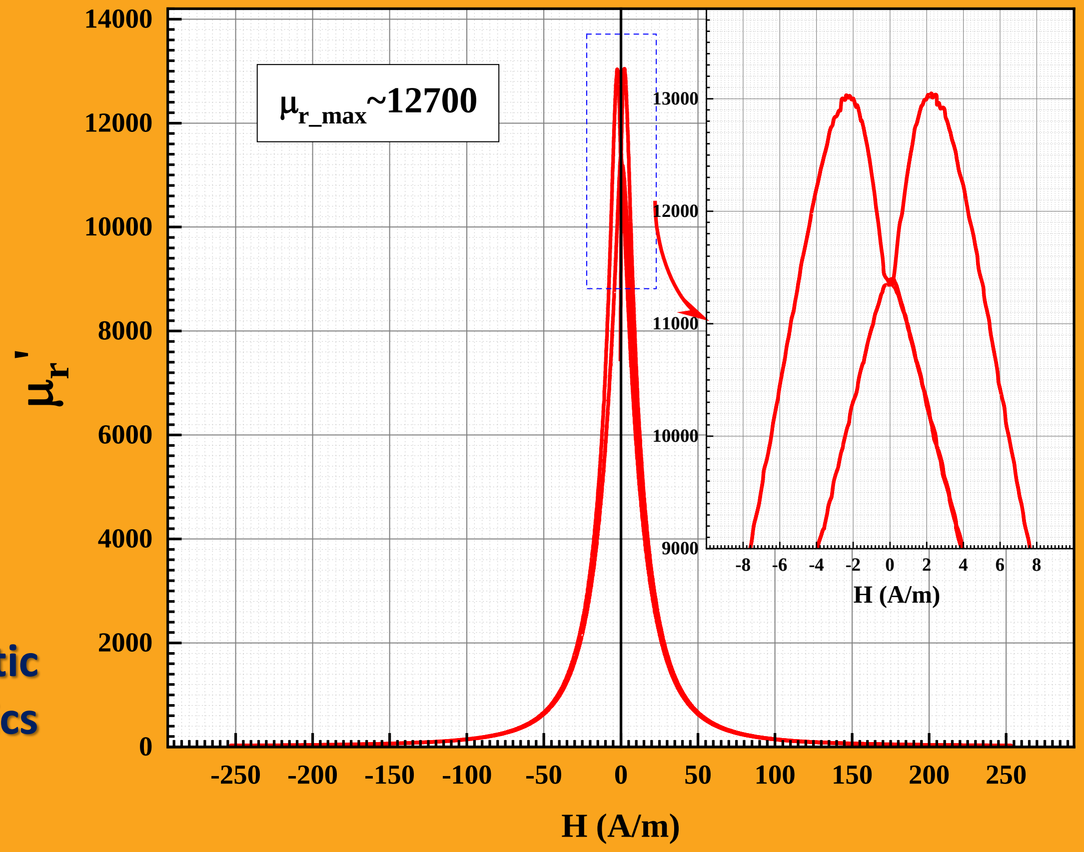


Fig. A family of AC hysteresis loops for grain-oriented electrical steel (B_R denotes *remanence* and H_C is the *coercivity*). Courtesy Zureks (Wikipedia)

Measuring the magnetic permeability



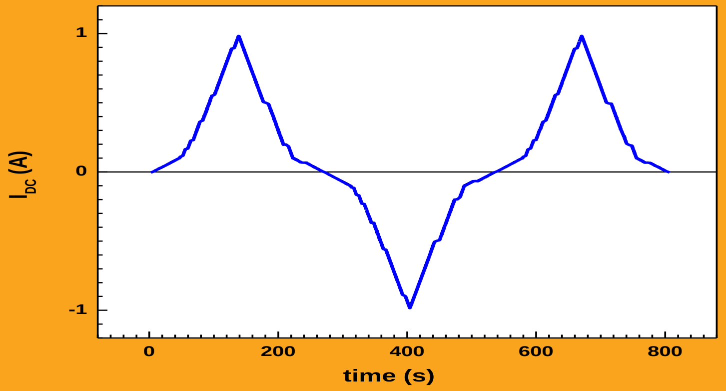


DC current profile and magnetic permeability of Magnetics ZW44715TC

From permeability to B-H hysteresis loop

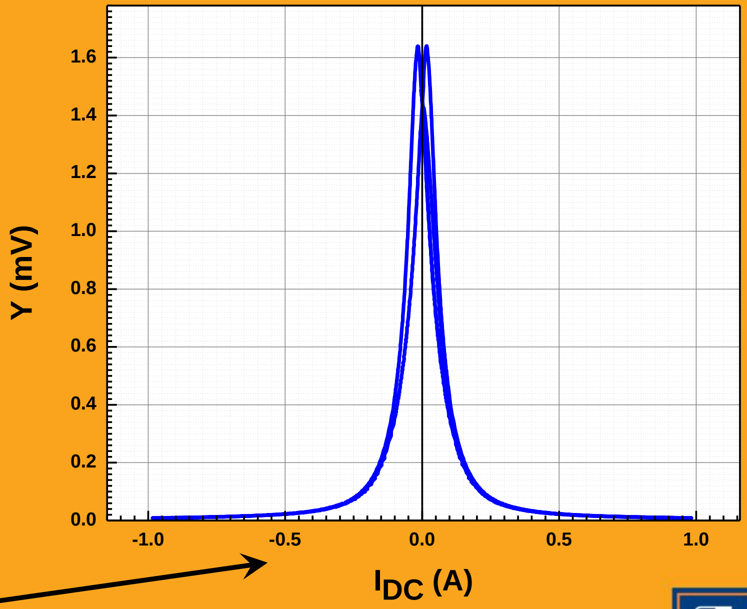
Step#1. Performing one fast IDC scan the based on the result preparing the "smart" IDC profile

ECE storeroom unknown material Sample #5



Step#2. Performing precise scan the. Plotting raw data based

Voltage units measured by SR830



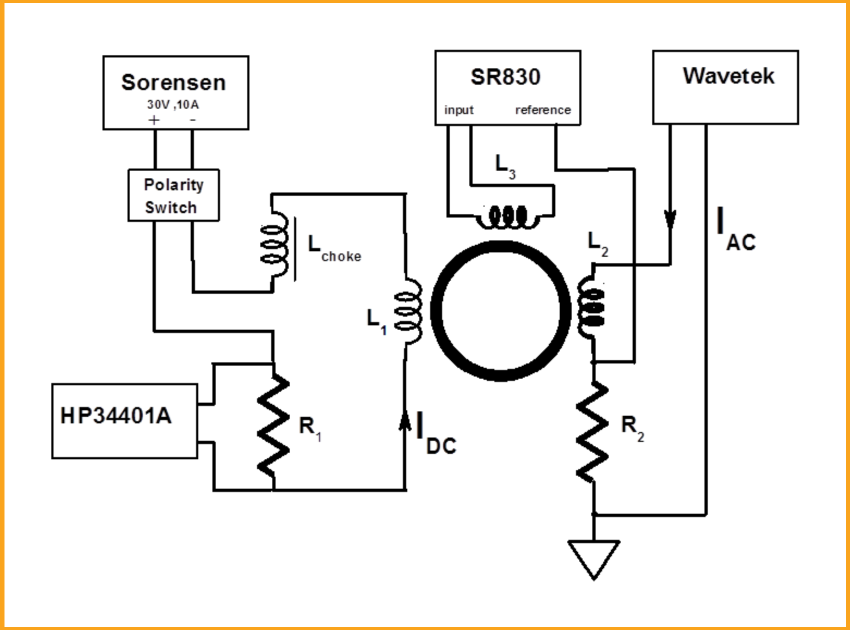
Current in primary coil in A

From permeability to B-H hysteresis loop

Step#3. What we are measuring?
Calibration.

Lock-in measures emf on the pickup coil

$$V_{lock-in} = -\frac{d\Phi}{dt}; \Phi = \vec{B} \bullet \vec{S}$$

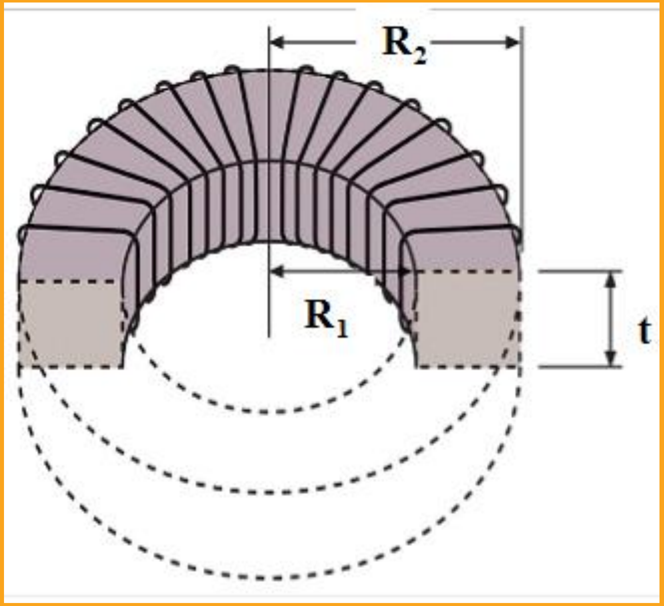


Here Ip is ac current in primary coil L3; $I_p = \frac{V_0 \sin(\omega t)}{R_2}$

From permeability to B-H hysteresis loop

Step#3. What we are measuring?
Calibration.

Primary coil of N_p turns supplied by current I_p creates magnetic field H and flux $d\Phi$



For toroid: $H = \frac{N_p I_p}{2\pi r}$

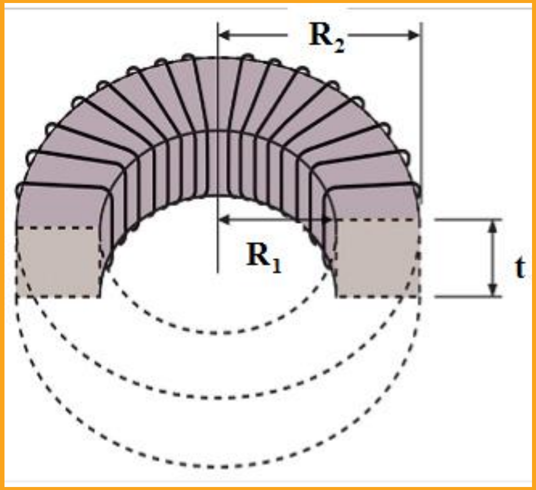
$R_2 < r < R_1$

$$d\Phi = \mu \int \vec{H} \cdot d\vec{a} = \frac{\mu\, I\, N\, t}{2\pi} \int_{R_1}^{R_2} \frac{dr}{r} = \frac{\mu\, I\, N\, t}{2\pi} \ln \frac{R_2}{R_1}$$

da=dr*t

From permeability to B-H hysteresis loop

Step#3. What we are measuring?
Calibration.



Total flux detected by pickup coil:

$$\Phi = N_{pickup} d\Phi = \frac{\mu N_{pickup} N_p I_p t}{2\pi} \ln \frac{R_2}{R_1}$$

Np and Ip number of turns of AC primary coil and AC rms current

Inductance of the toroid:

$$L = \frac{\Phi}{I}; \quad L = \mu_r L_0 = (\mu' - i\mu'')L_0$$

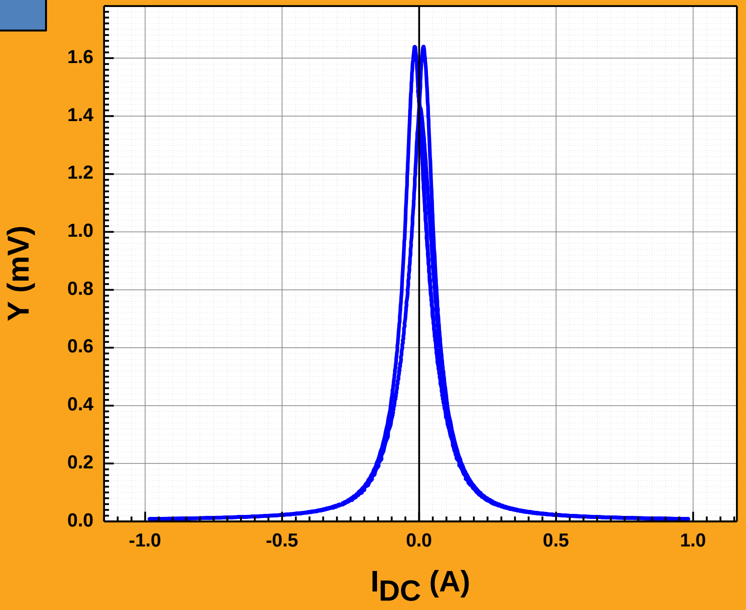
$$L_0 = \frac{\mu_0 N_{pickup} N_p t}{2\pi} \ln \frac{R_2}{R_1}$$

From permeability to B-H hysteresis loop

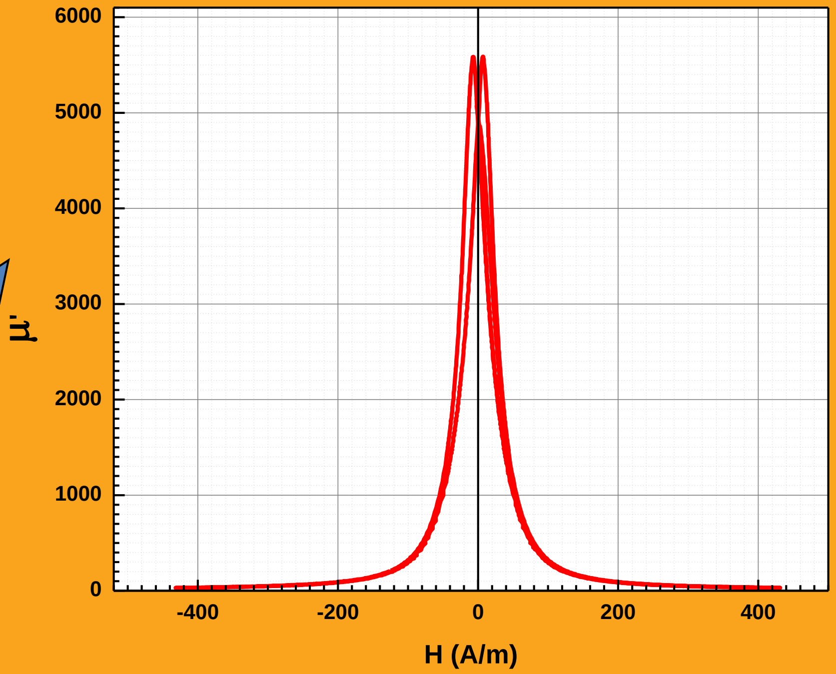
$$V_{lock-in} = \mu_r L_0 \frac{dI_p}{dt}$$

$$\frac{dI_p}{dt} = \frac{V_0}{R_2}\omega\cos(\omega t)$$

$\sim \omega$!

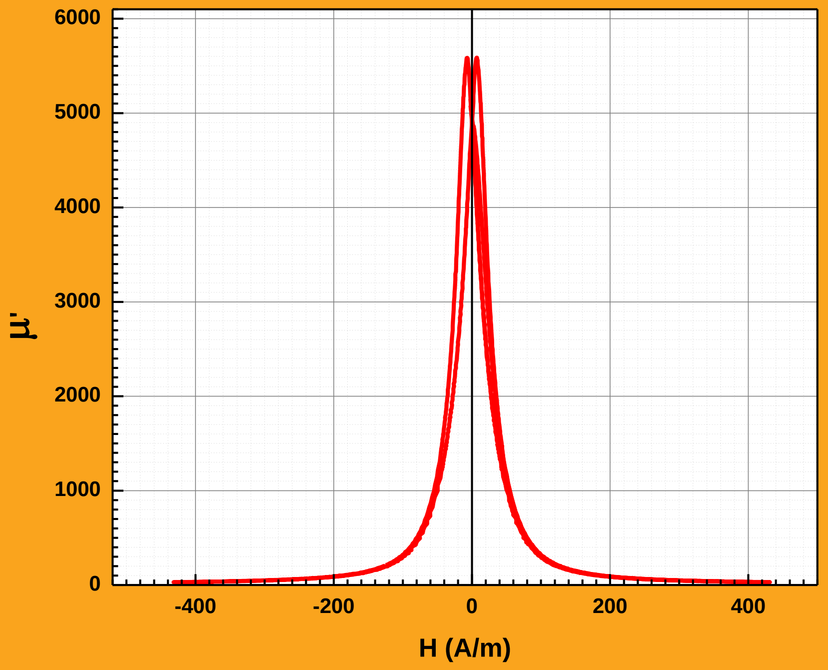


$\sim \omega$



$$H_0 = \frac{N_p I_{DC}}{2\pi r}$$

From permeability to B-H hysteresis loop

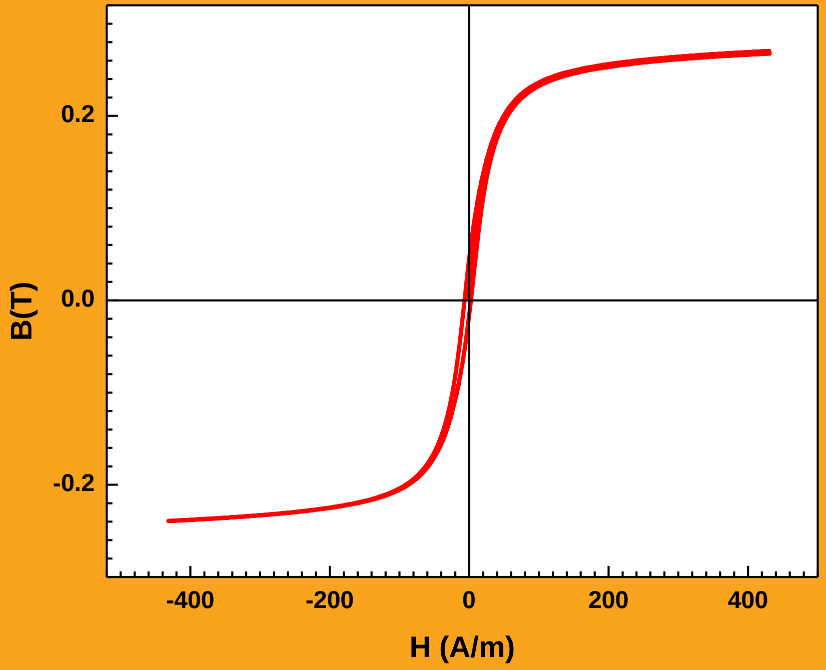


Step#4. From μ_r(H) to B-H

$$\mu(H_0) = \mu_0 \mu_r (H_0) = \left.\frac{dB}{dH}\right|_{H_0}$$

After integrating →

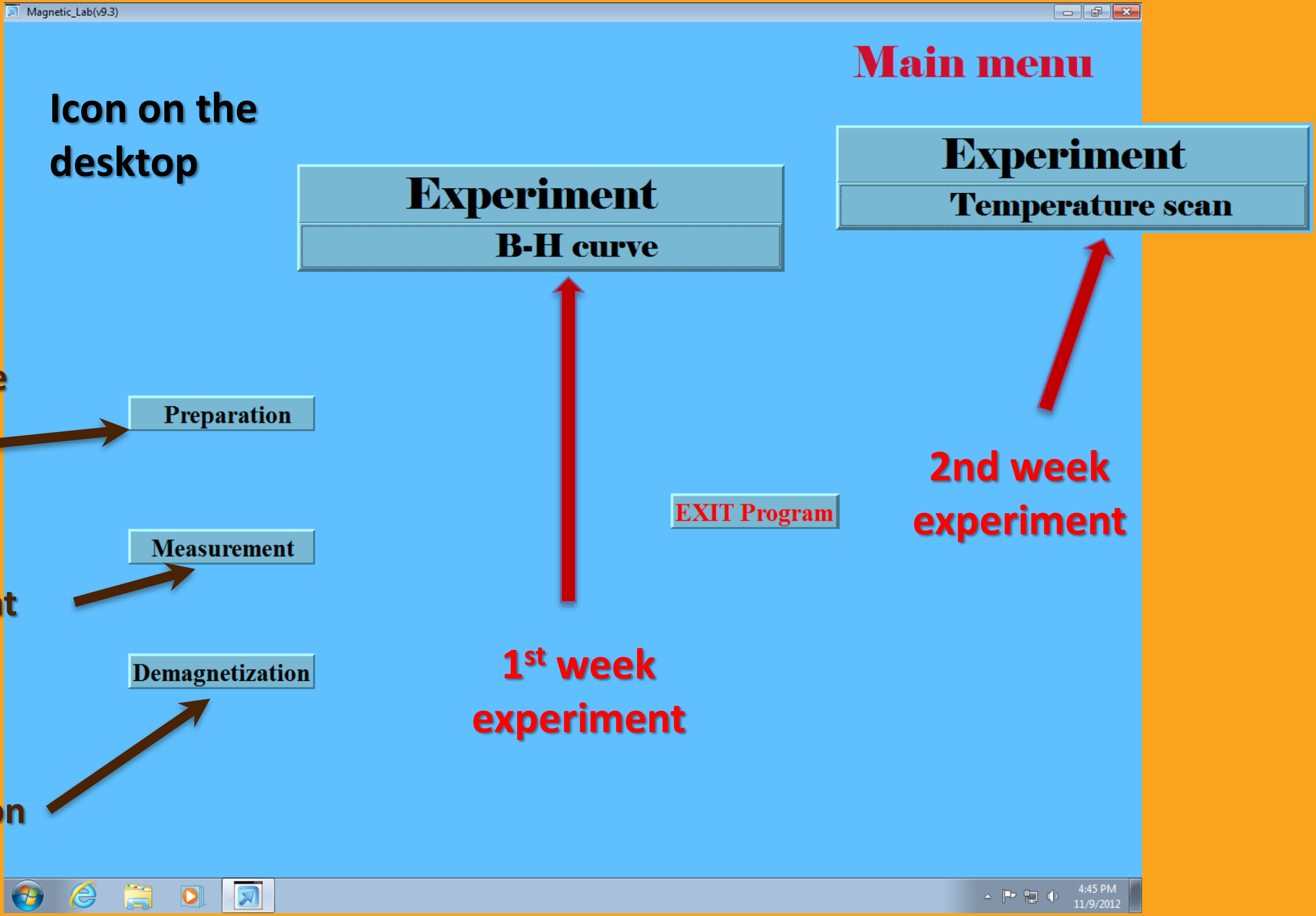
$$B(H) = \mu_0 \int \mu_r (H) dH$$



Software issue

Magnetic Lab v9.2

Icon on the desktop



Main menu

Preparation of the profile of the experiment

B-H measurement

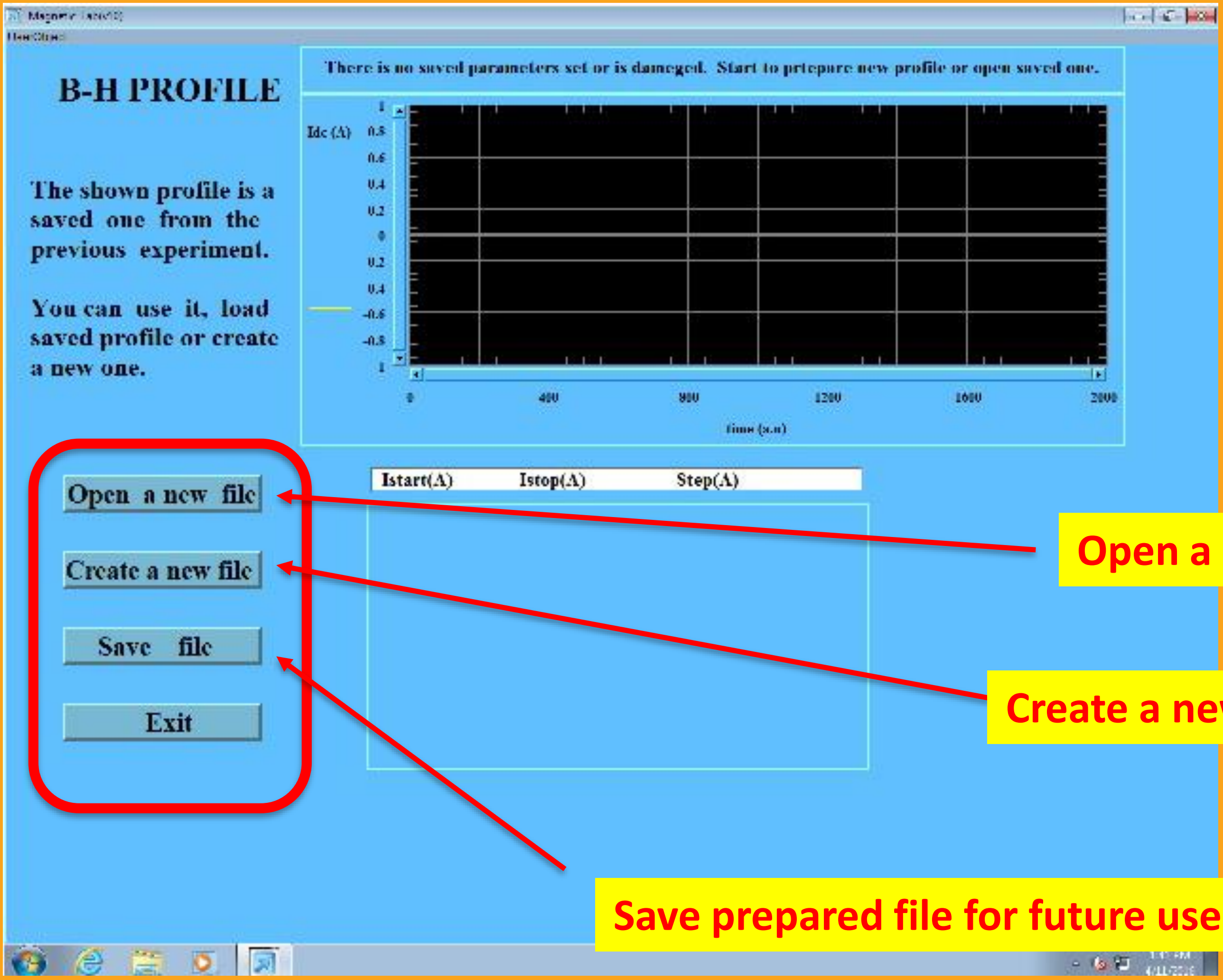
Demagnetization

1st week experiment

2nd week experiment

Software issue

Measuring profile preparation. Using profile template



There is no saved parameters set or is dameged. Start to prtepare new profile or open saved one.

B-H PROFILE

The shown profile is a saved one from the previous experiment.

You can use it, load saved profile or create a new one.

Istart(A)	Istop(A)	Step(A)

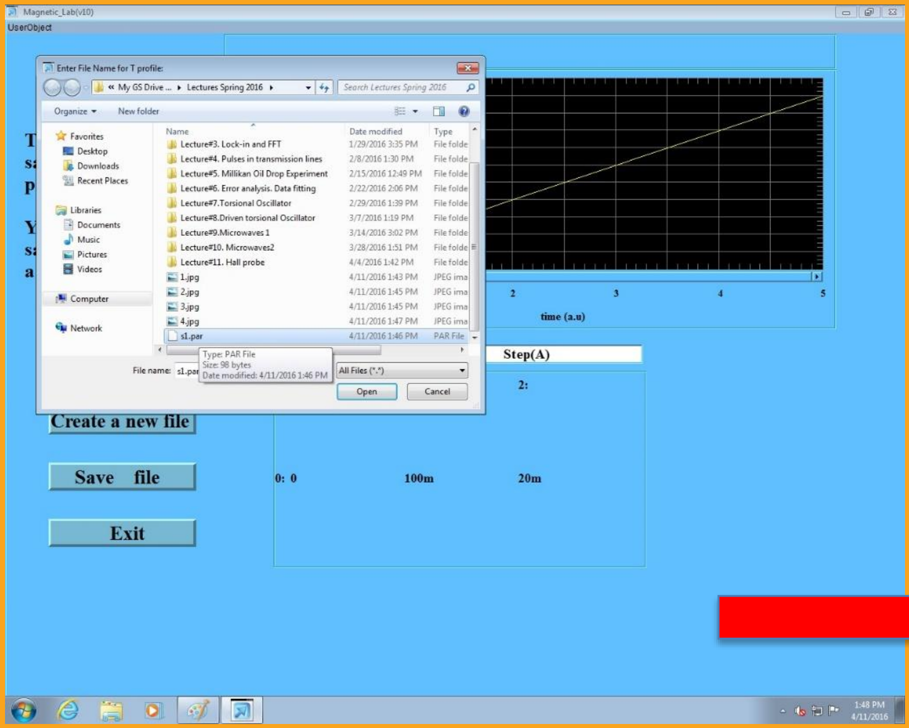
Open a new file

Create a new file

Save prepared file for future use

Software issue

Measuring profile preparation. Using profile template.



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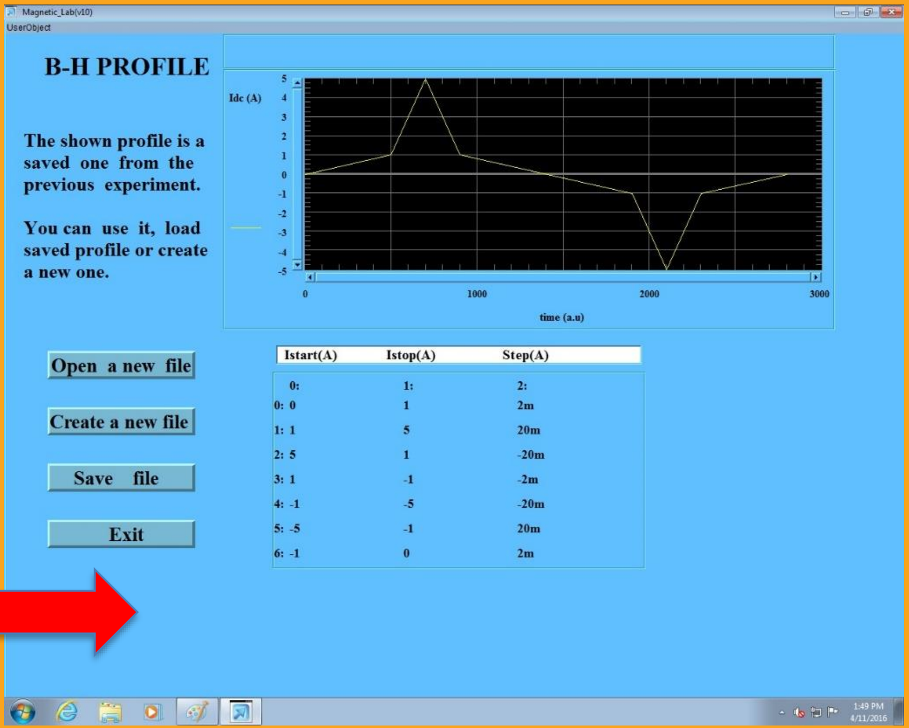
Lecture#3. Lock-in and FFT	1/29/2016 3:35 PM	File folde
Lecture#4. Pulses in transmission lines	2/8/2016 1:30 PM	File folde
Lecture#5. Millikan Oil Drop Experiment	2/15/2016 12:49 PM	File folde
Lecture#6. Error analysis. Data fitting	2/22/2016 2:06 PM	File folde
Lecture#7.Torsional Oscillator	2/29/2016 1:39 PM	File folde
Lecture#8.Driven torsional Oscillator	3/7/2016 1:19 PM	File folde
Lecture#9.Microwaves 1	3/14/2016 3:02 PM	File folde
Lecture#10. Microwaves2	3/28/2016 1:51 PM	File folde
Lecture#11. Hall probe	4/4/2016 1:42 PM	File folde
1.jpg	4/11/2016 1:43 PM	JPEG ima
2.jpg	4/11/2016 1:45 PM	JPEG ima
3.jpg	4/11/2016 1:45 PM	JPEG ima
4.jpg	4/11/2016 1:47 PM	JPEG ima
s1.par	4/11/2016 1:46 PM	PAR File

Type: PAR File
Size: 98 bytes
Date modified: 4/11/2016 1:46 PM

File name: s1.par

All Files (*.*)

		Step(A)
		2:
0: 0	100m	20m



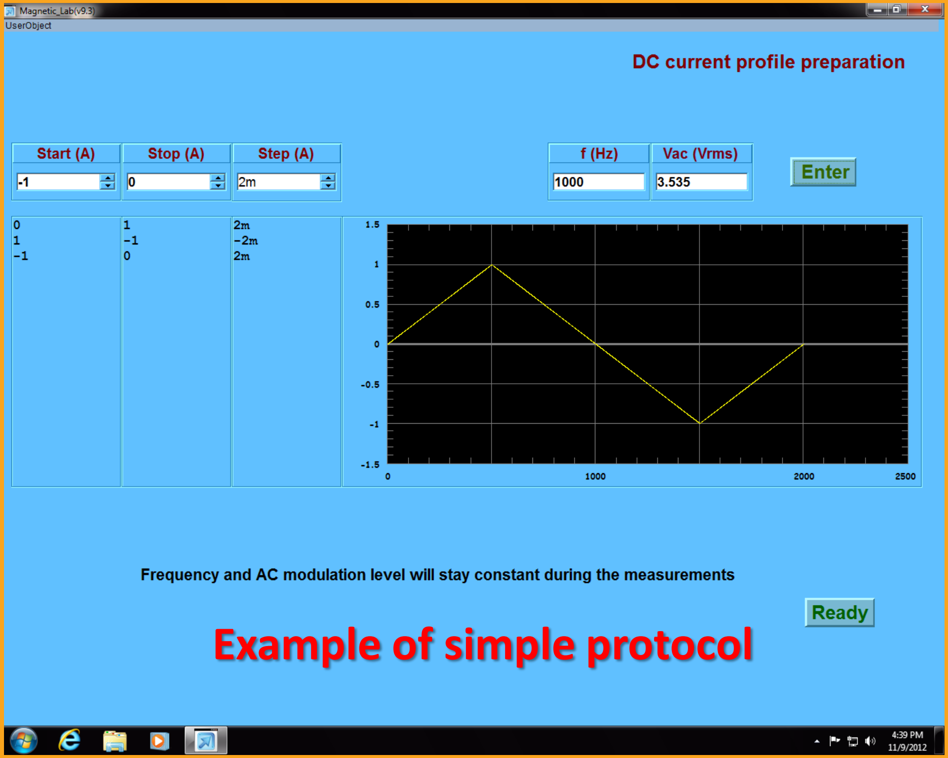
B-H PROFILE

The shown profile is a saved one from the previous experiment.

You can use it, load saved profile or create a new one.

	Istart(A)	Istop(A)	Step(A)
	0:	1:	2:
0:	0	1	2m
1:	1	5	20m
2:	5	1	-20m
3:	1	-1	-2m
4:	-1	-5	-20m
5:	-5	-1	20m
6:	-1	0	2m

Software issue



Magnetic_Lab(v9.3)

UserObject

DC current profile preparation

Start (A)	Stop (A)	Step (A)
-1	0	2m
0 1 -1	1 -1 0	2m -2m 2m

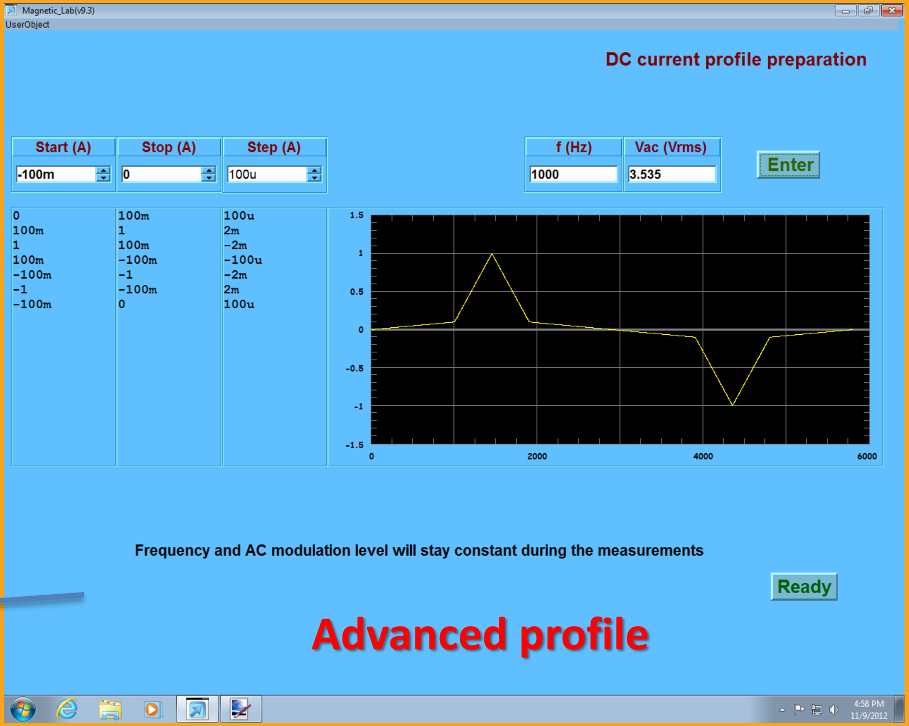
f (Hz): 1000

Vac (Vrms): 3.535

Frequency and AC modulation level will stay constant during the measurements

Example of simple protocol

Measuring profile preparation



Magnetic_Lab(v9.3)

UserObject

DC current profile preparation

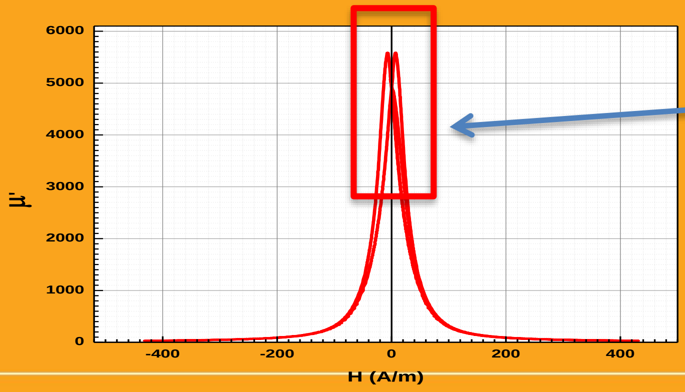
Start (A)	Stop (A)	Step (A)
-100m	0	100u
0 100m 1 100m -100m -1 -100m	100m 1 100m -100m -1 -100m 0	100u 2m -2m -100u -2m 2m 100u

f (Hz): 1000

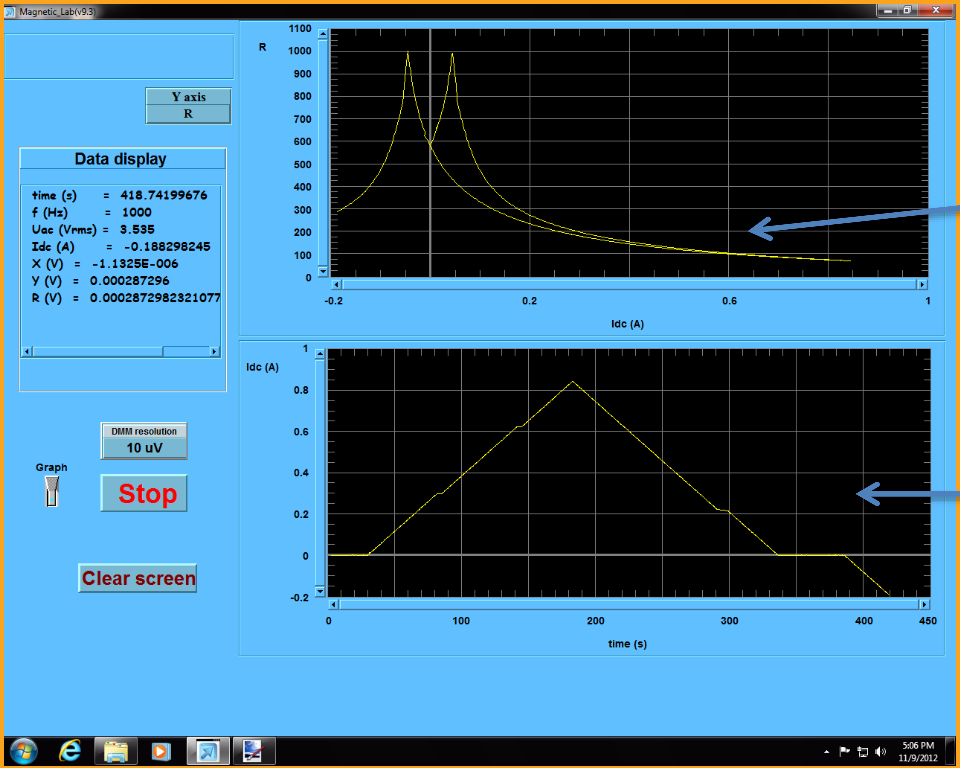
Vac (Vrms): 3.535

Frequency and AC modulation level will stay constant during the measurements

Advanced profile



Software issue



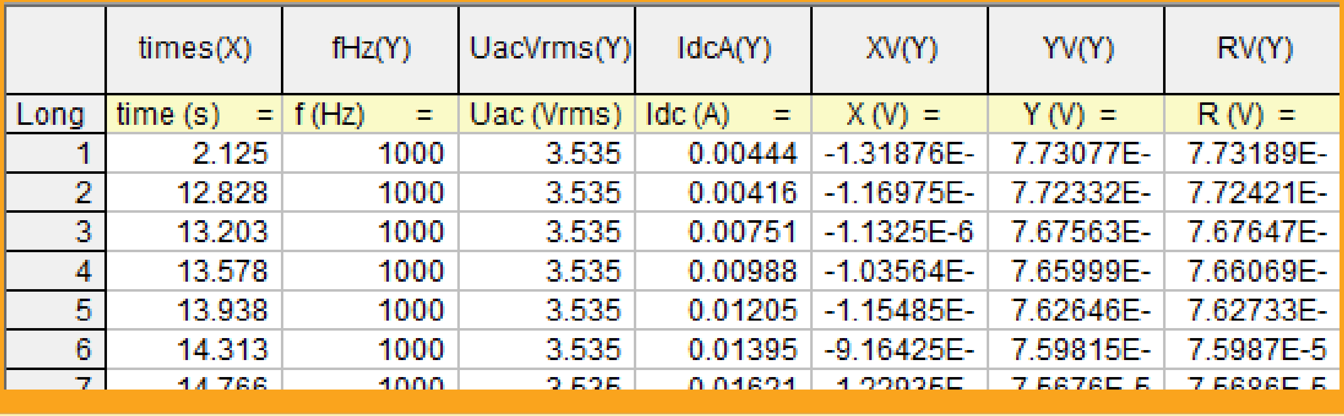
time (s) = 418.74199676
f (Hz) = 1000
Uac (Vrms) = 3.535
Idc (A) = -0.188298245
X (V) = -1.1325E-006
Y (V) = 0.000287296
R (V) = 0.0002872982321077

Measurement Window

Lock-in amplifier response

The profile of the applied DC current

Structure of the data file (B-H experiment)



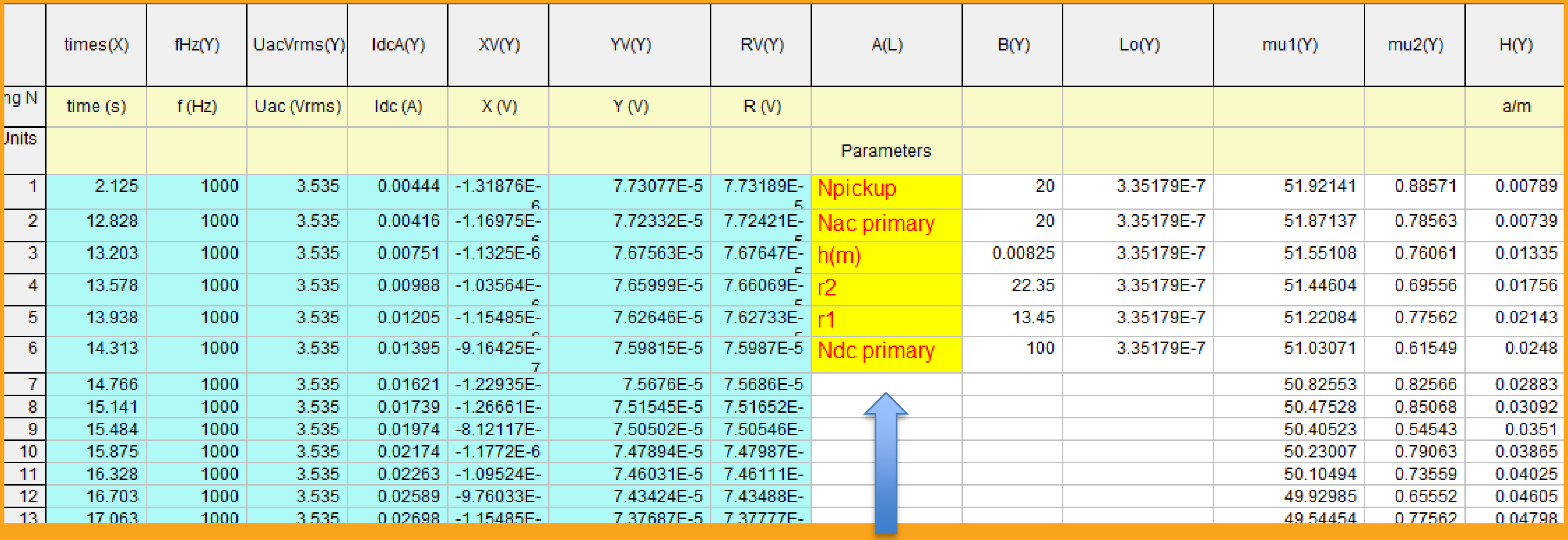
	times(X)	fHz(Y)	UacVrms(Y)	IdcA(Y)	XV(Y)	YV(Y)	RV(Y)
Long	time (s) =	f (Hz) =	Uac (Vrms)	Idc (A) =	X (V) =	Y (V) =	R (V) =
1	2.125	1000	3.535	0.00444	-1.31876E-	7.73077E-	7.73189E-
2	12.828	1000	3.535	0.00416	-1.16975E-	7.72332E-	7.72421E-
3	13.203	1000	3.535	0.00751	-1.1325E-6	7.67563E-	7.67647E-
4	13.578	1000	3.535	0.00988	-1.03564E-	7.65999E-	7.66069E-
5	13.938	1000	3.535	0.01205	-1.15485E-	7.62646E-	7.62733E-
6	14.313	1000	3.535	0.01395	-9.16425E-	7.59815E-	7.5987E-5
7	14.766	1000	3.535	0.01621	-1.22035E-	7.5676E-5	7.5686E-5

Data analysis using Origin

To calculate the permeability better to use the template :

\\engr-file-03\phyinst\APL Courses\PHYCS401\Common\Origin templates\AC magnetic Lab\MU_CALCULATION.otwu

It does not contain the equations – you have to write them



	times(X)	fHz(Y)	UacVrms(Y)	IdcA(Y)	XV(Y)	YV(Y)	RV(Y)	A(L)	B(Y)	Lo(Y)	mu1(Y)	mu2(Y)	H(Y)
ng N	time (s)	f (Hz)	Uac (Vrms)	Idc (A)	X (V)	Y (V)	R (V)						a/m
Jnits								Parameters					
1	2.125	1000	3.535	0.00444	-1.31876E-6	7.73077E-5	7.73189E-5	Npickup	20	3.35179E-7	51.92141	0.88571	0.00789
2	12.828	1000	3.535	0.00416	-1.16975E-	7.72332E-5	7.72421E-	Nac primary	20	3.35179E-7	51.87137	0.78563	0.00739
3	13.203	1000	3.535	0.00751	-1.1325E-6	7.67563E-5	7.67647E-	h(m)	0.00825	3.35179E-7	51.55108	0.76061	0.01335
4	13.578	1000	3.535	0.00988	-1.03564E-	7.65999E-5	7.66069E-	r2	22.35	3.35179E-7	51.44604	0.69556	0.01756
5	13.938	1000	3.535	0.01205	-1.15485E-	7.62646E-5	7.62733E-	r1	13.45	3.35179E-7	51.22084	0.77562	0.02143
6	14.313	1000	3.535	0.01395	-9.16425E-7	7.59815E-5	7.5987E-5	Ndc primary	100	3.35179E-7	51.03071	0.61549	0.0248
7	14.766	1000	3.535	0.01621	-1.22935E-	7.5676E-5	7.5686E-5				50.82553	0.82566	0.02883
8	15.141	1000	3.535	0.01739	-1.26661E-	7.51545E-5	7.51652E-				50.47528	0.85068	0.03092
9	15.484	1000	3.535	0.01974	-8.12117E-	7.50502E-5	7.50546E-				50.40523	0.54543	0.0351
10	15.875	1000	3.535	0.02174	-1.1772E-6	7.47894E-5	7.47987E-				50.23007	0.79063	0.03865
11	16.328	1000	3.535	0.02263	-1.09524E-	7.46031E-5	7.46111E-				50.10494	0.73559	0.04025
12	16.703	1000	3.535	0.02589	-9.76033E-	7.43424E-5	7.43488E-				49.92985	0.65552	0.04605
13	17.063	1000	3.535	0.02698	-1.15485E-	7.37687E-5	7.37777E-				49.54454	0.77562	0.04798

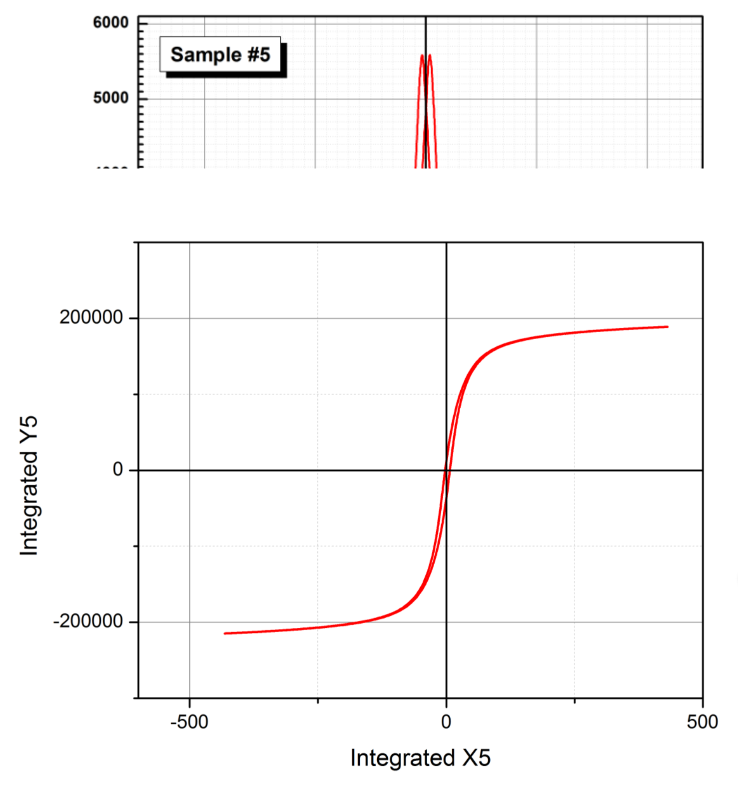
Raw data

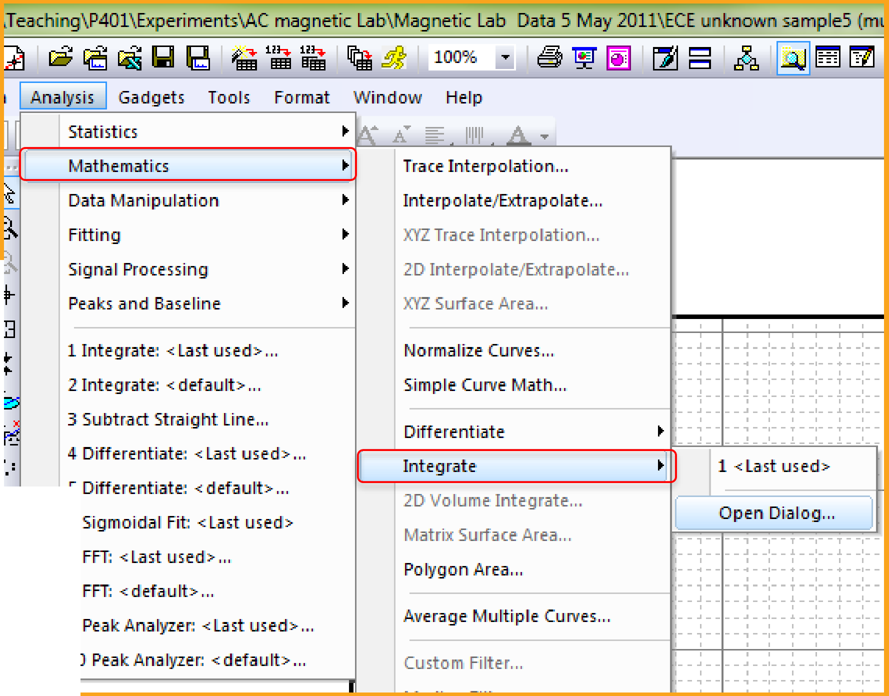
Parameters

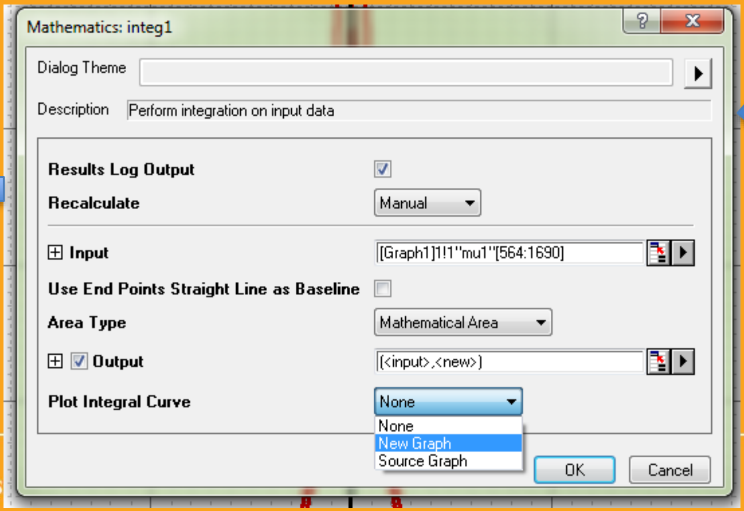
Calculated results

Data analysis using Origin. Integrating.

$$B(H) = \mu_0 \int \mu_r(H)\,dH$$







Dialog Theme

Description: Perform integration on input data

Results Log Output ☑

Recalculate: Manual

⊞ Input: [Graph1]1!1"mu1"[564:1690]

Use End Points Straight Line as Baseline ☐

Area Type: Mathematical Area

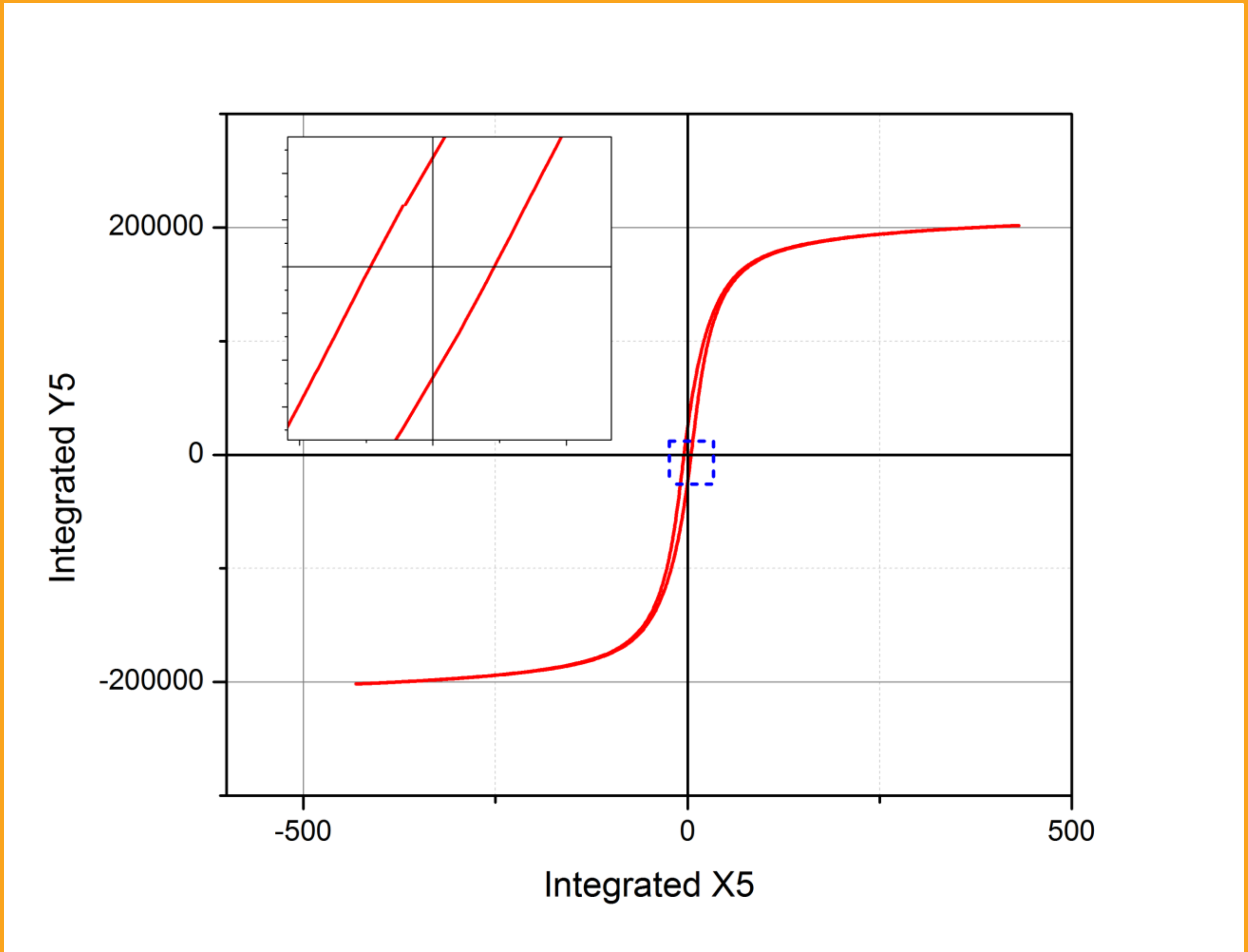
⊞ ☑ Output: [<input>,<new>]

Plot Integral Curve: None

None
New Graph
Source Graph

Data analysis using Origin. Integrating.

$$B(H) = \mu_0 \int \mu_r(H)\,dH + offset$$



References

- **Information about magnetic materials can be found in :**

\\engr-file-03\phyinst\APL Courses\PHYCS401\Experiments\AC_Magnetization\Magnetic Materials

- **SR830 manual: \\engr-file-03\phyinst\APL Courses\PHYCS401\Common\EquipmentManuals\SR830m.pdf**