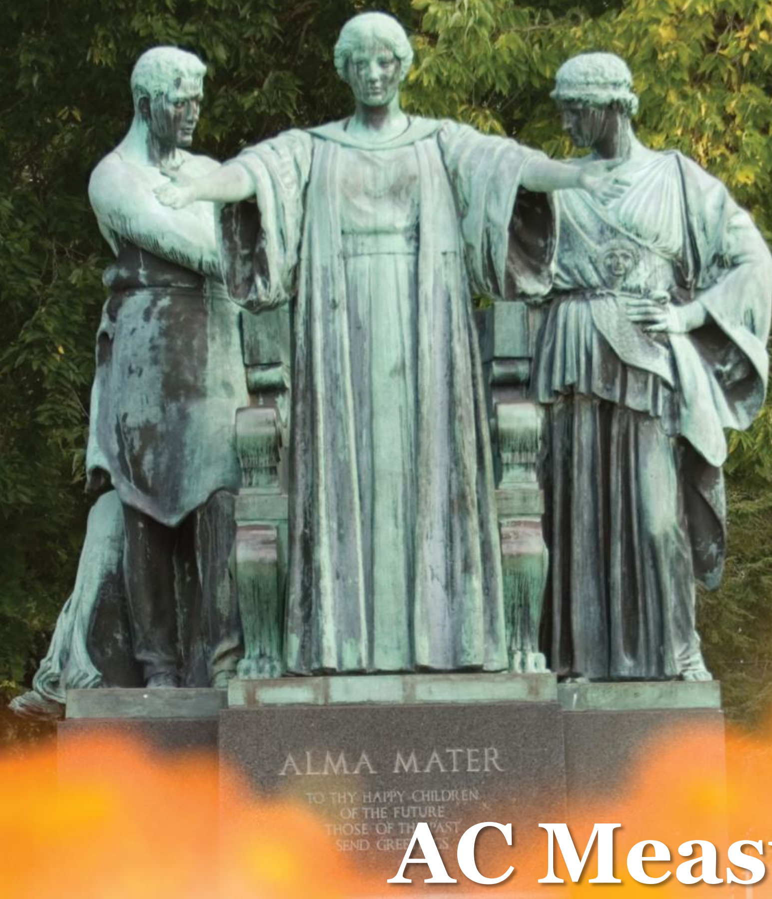


UNIVERSITY OF ILLINOIS
AT URBANA-CHAMPAIGN

AC Measurement of Magnetic Susceptibility

Physics 401, Fall 2016

Eugene V. Colla

Outline

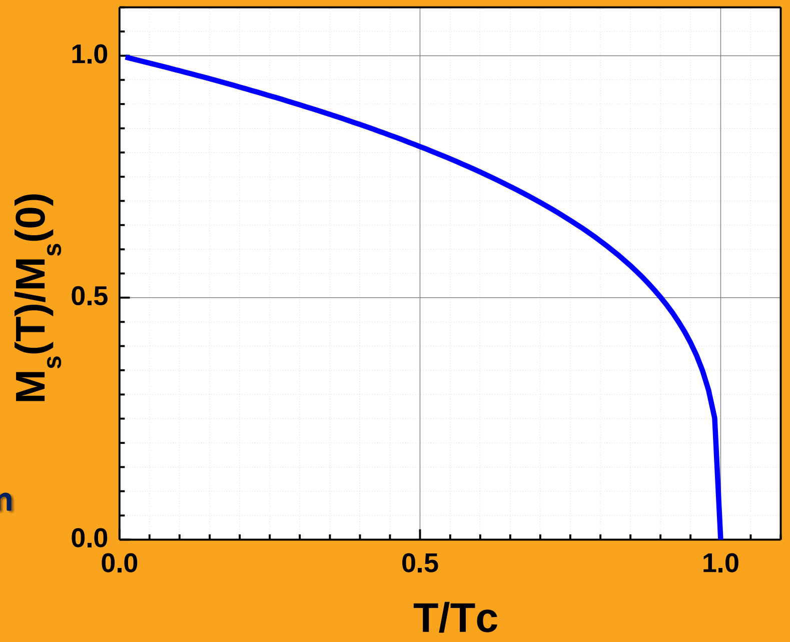
- Ferromagnetism
- Measurement of the magnetic properties of the materials
- Lab experimental setup and experiments
- Some results

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.

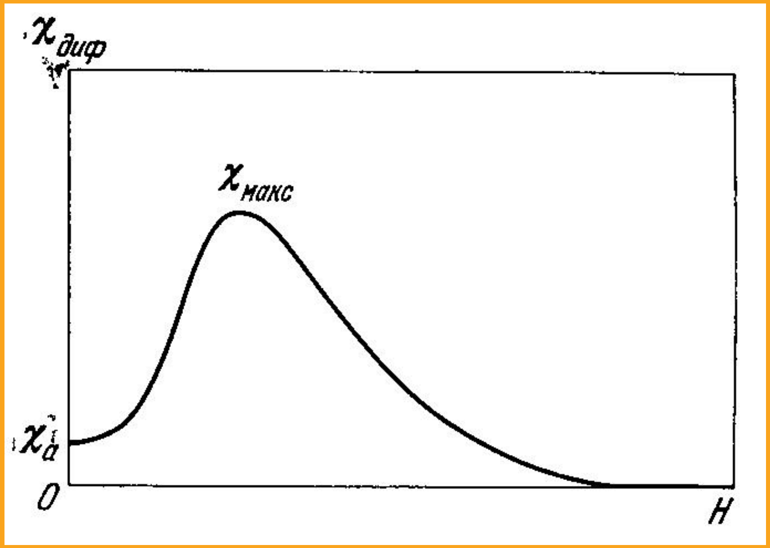
The main parameter of the ferromagnetic phase transition is spontaneous magnetization



Typical behavior of spontaneous magnetization as function of temperature

Ferromagnetic materials.

Aleksandr Stoletov
(1839 –1896)



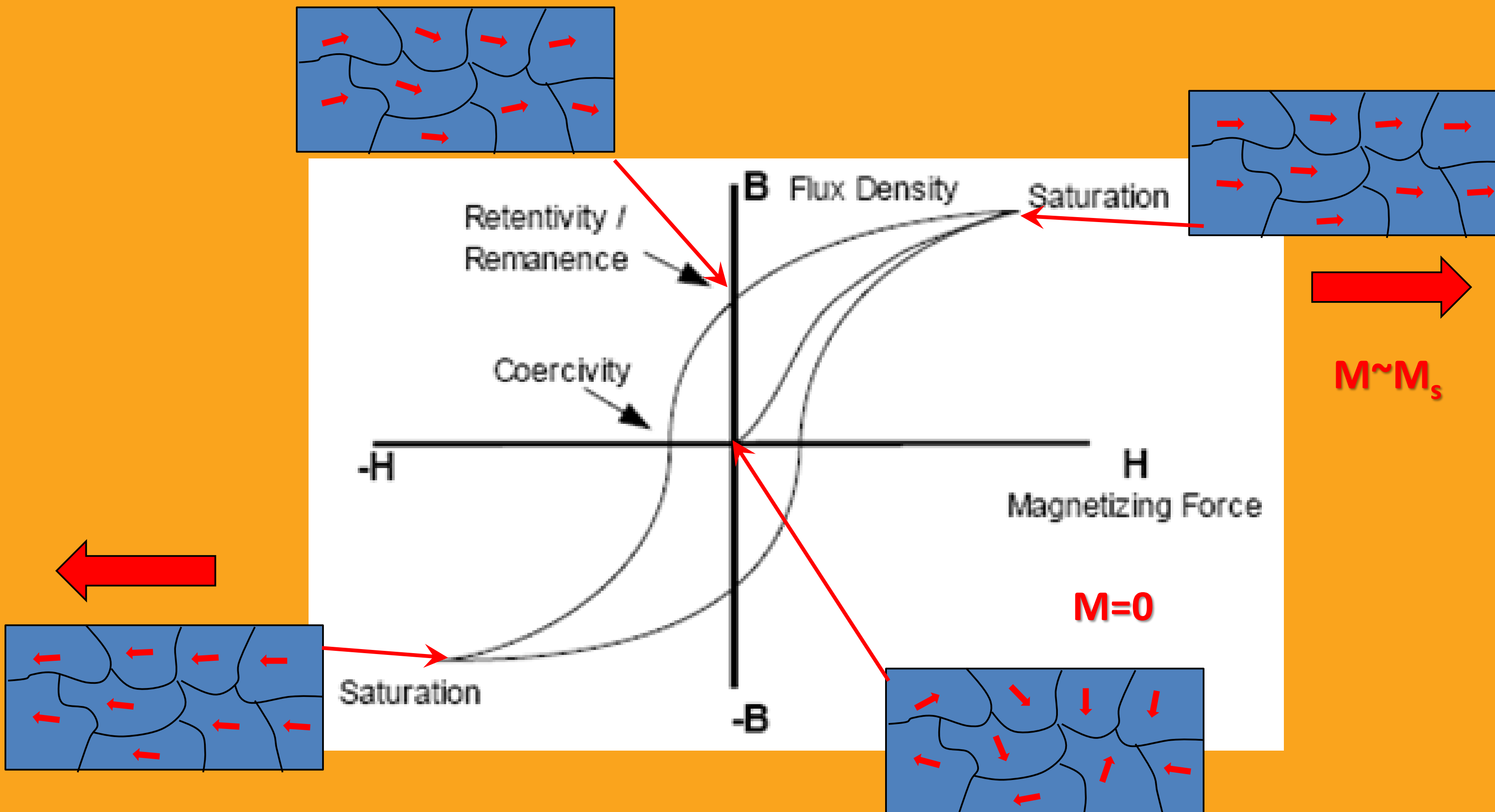
"Stoletov" curve

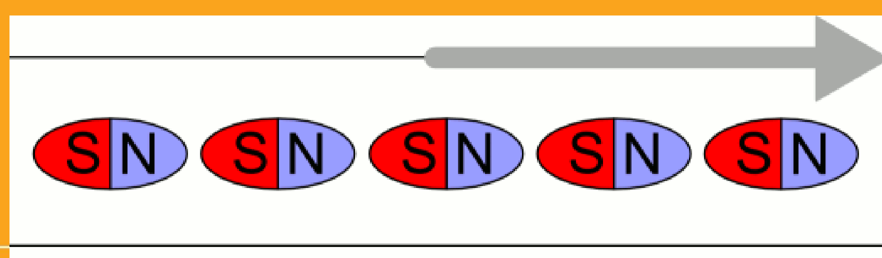
$$\chi = \frac{dM}{dH}$$

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

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

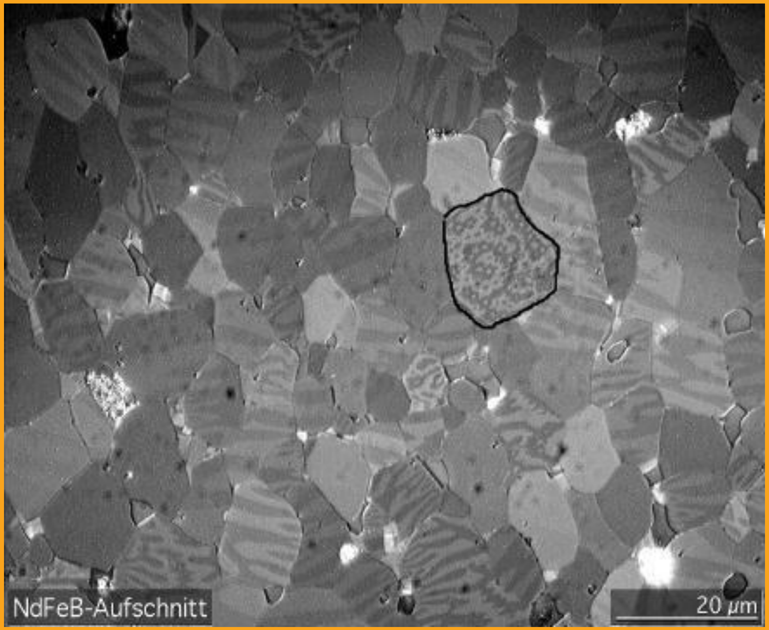
Domains. Hysteresis loop.





* Courtesy Wikipedia

Domains

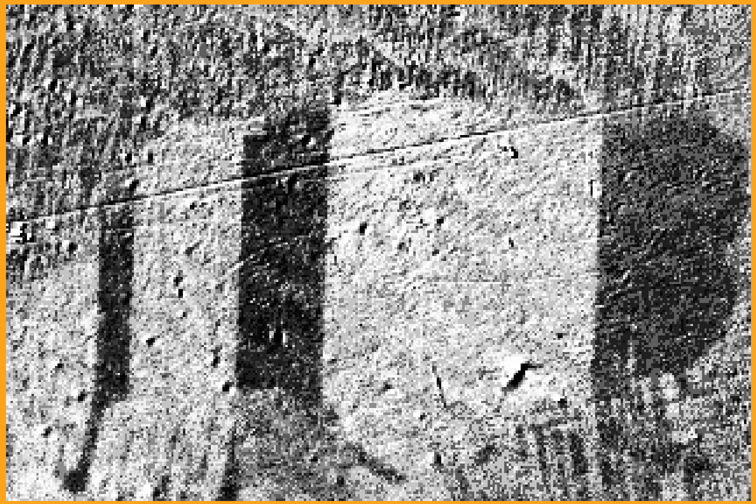


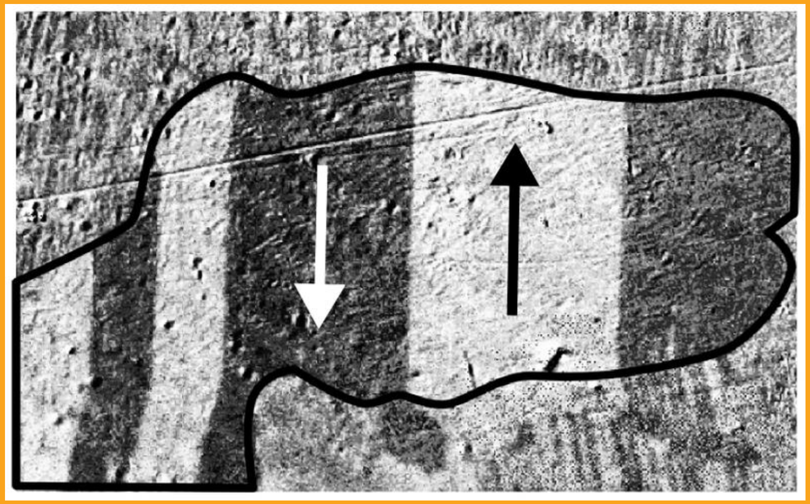
Several grains of NdFeB with magnetic domains made visible via contrast with a Kerr microscope.

Courtesy of Wikipedia

Kerr microscope
Courtesy of University of Uppsala (Sweden)

Domains

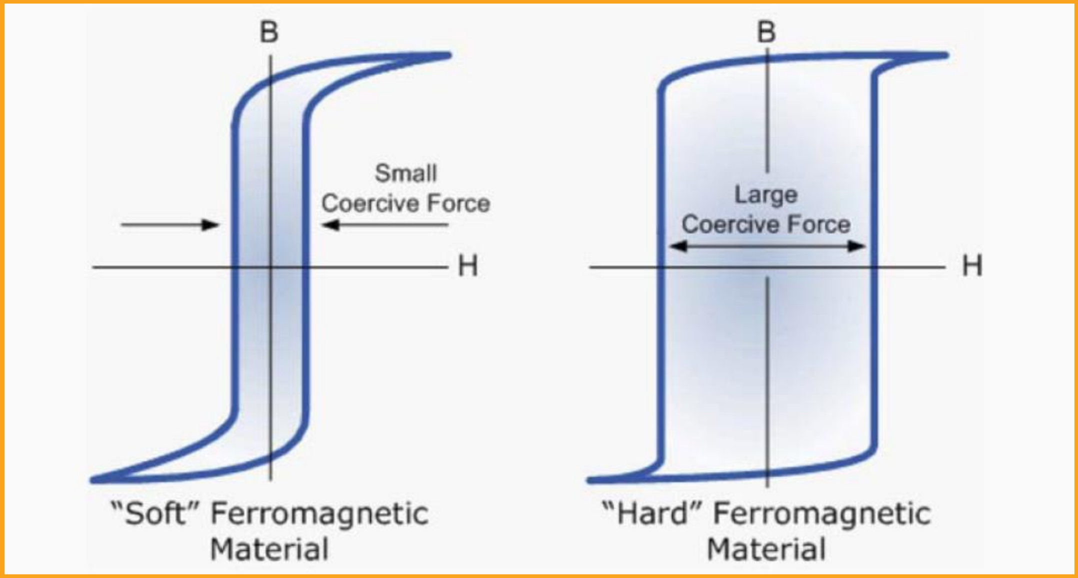




Moving domain walls in a grain of silicon steel caused by an increasing external magnetic field

Courtesy of Wikipedia

Hysteresis Loops. Remagnetization loses



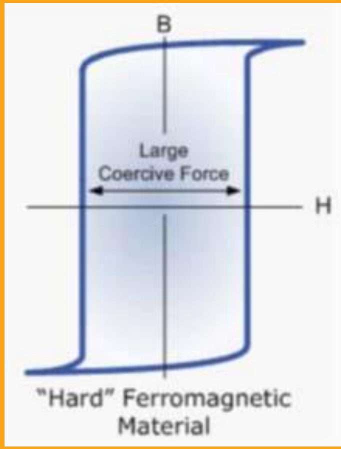
Energy of the magnetic field

$$W = V\int H dB$$

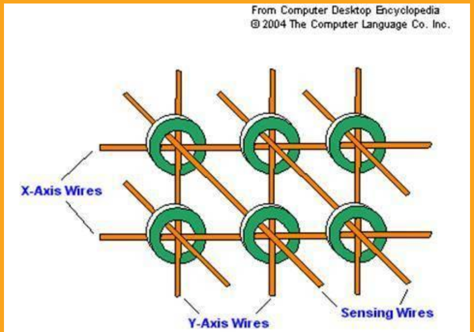
By cycling around the loop

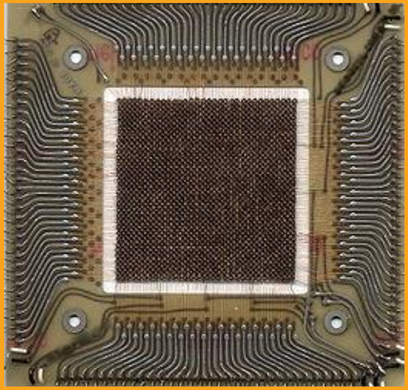
$$W_{loop} = V\oint H dB = V*Loop\_area$$

“Hard” materials. Application.



RAM memory

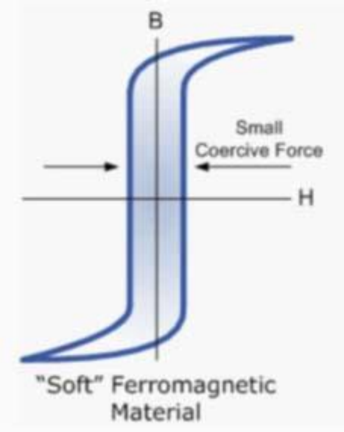




Permanent magnets

Hard drives, floppy, magnetic tape

“Soft” materials. Application.



Chokes, inductors

Power transformers

Magnetic Field, Susceptibility etc.

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

B – magnetic induction
M – magnetization, in general M(H)

$$M = \chi H$$

χ – magnetic susceptibility,
in general χ(H)

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

$$\mu_r = 1 + \chi$$

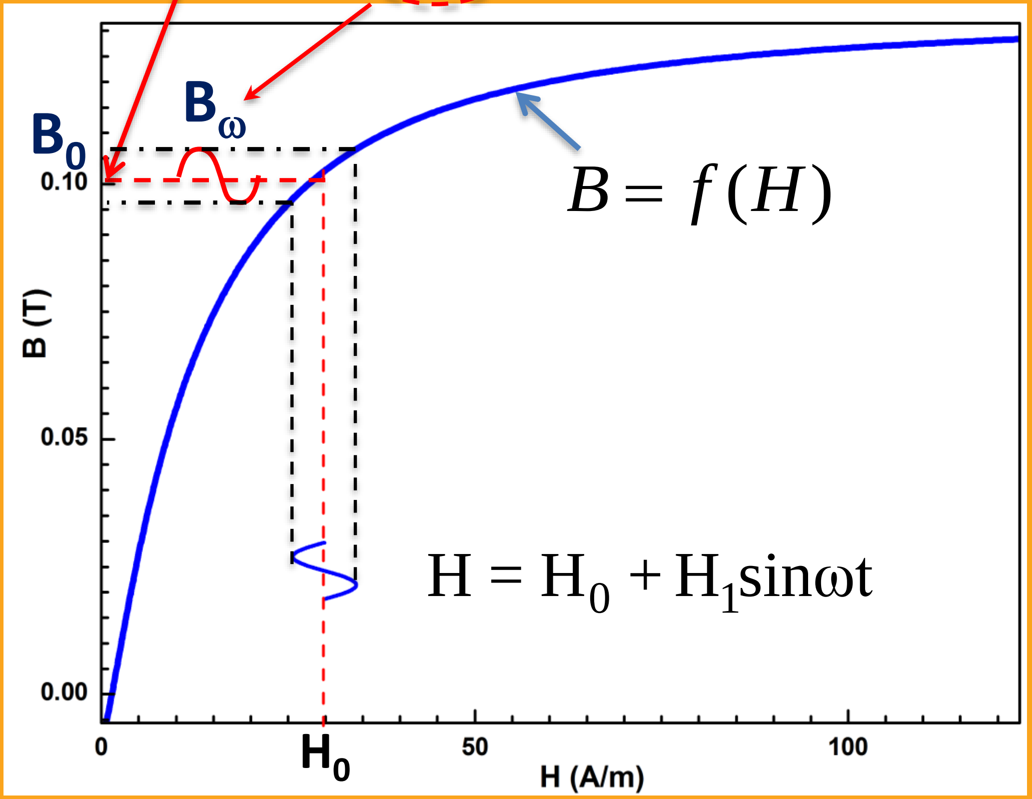
$$\mu = \mu_0 \mu_r = \frac{dB}{dH}; \quad \mu_r = \frac{1}{\mu_0} \frac{dB}{dH}$$

Modulation Spectroscopy

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

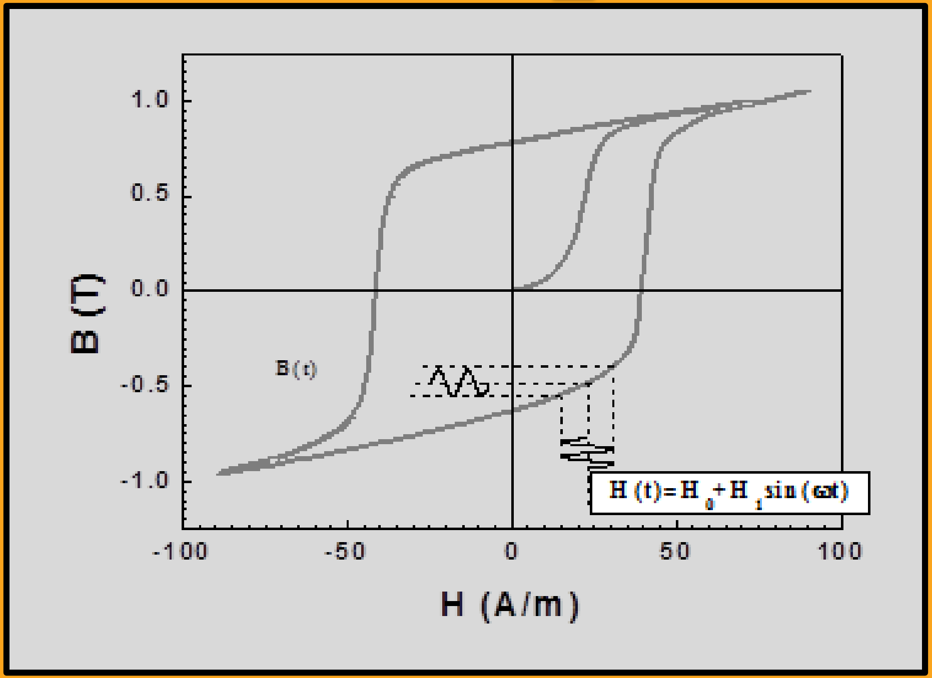
$$B = f(H_0) + \frac{df}{dH}(H_1 \sin\omega t) + \ldots$$

H_1=const



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

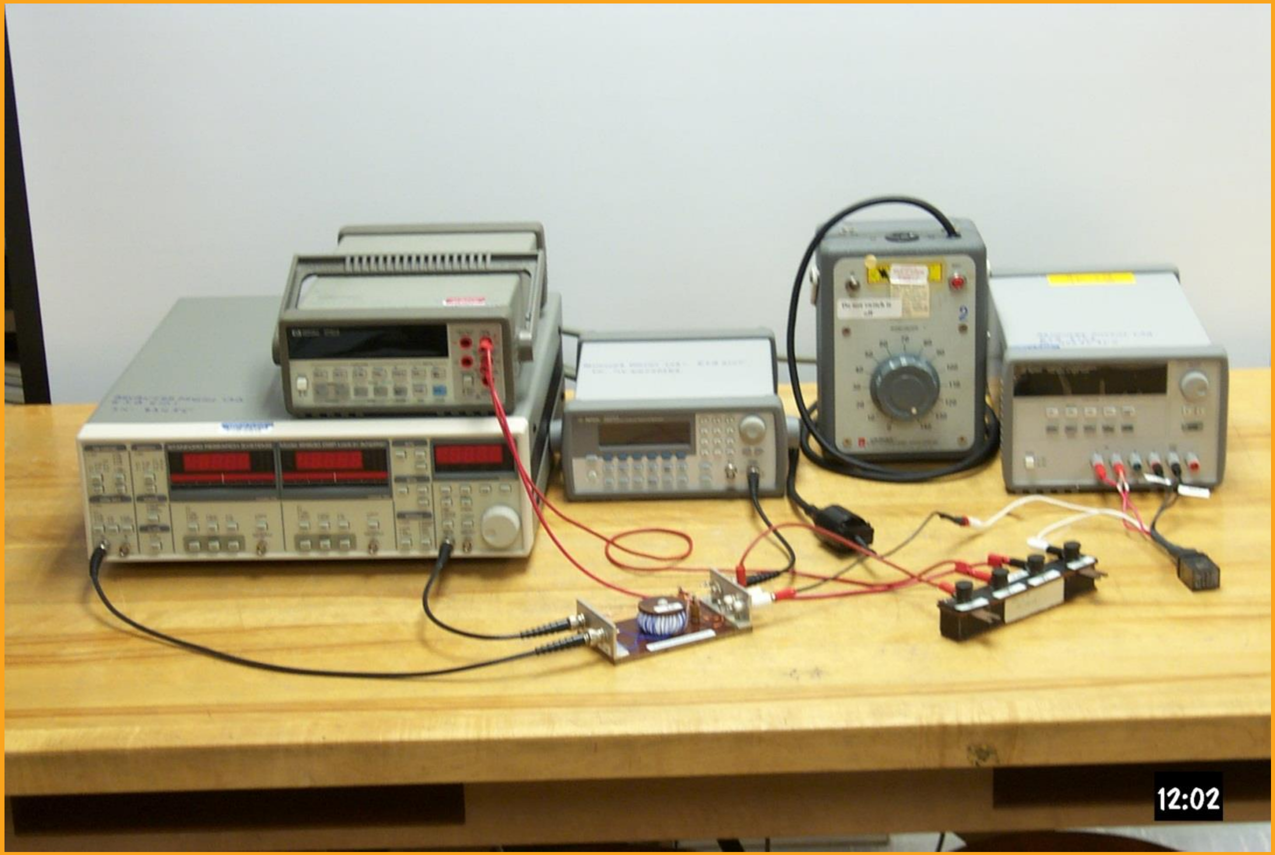
Measuring the magnetic permeability



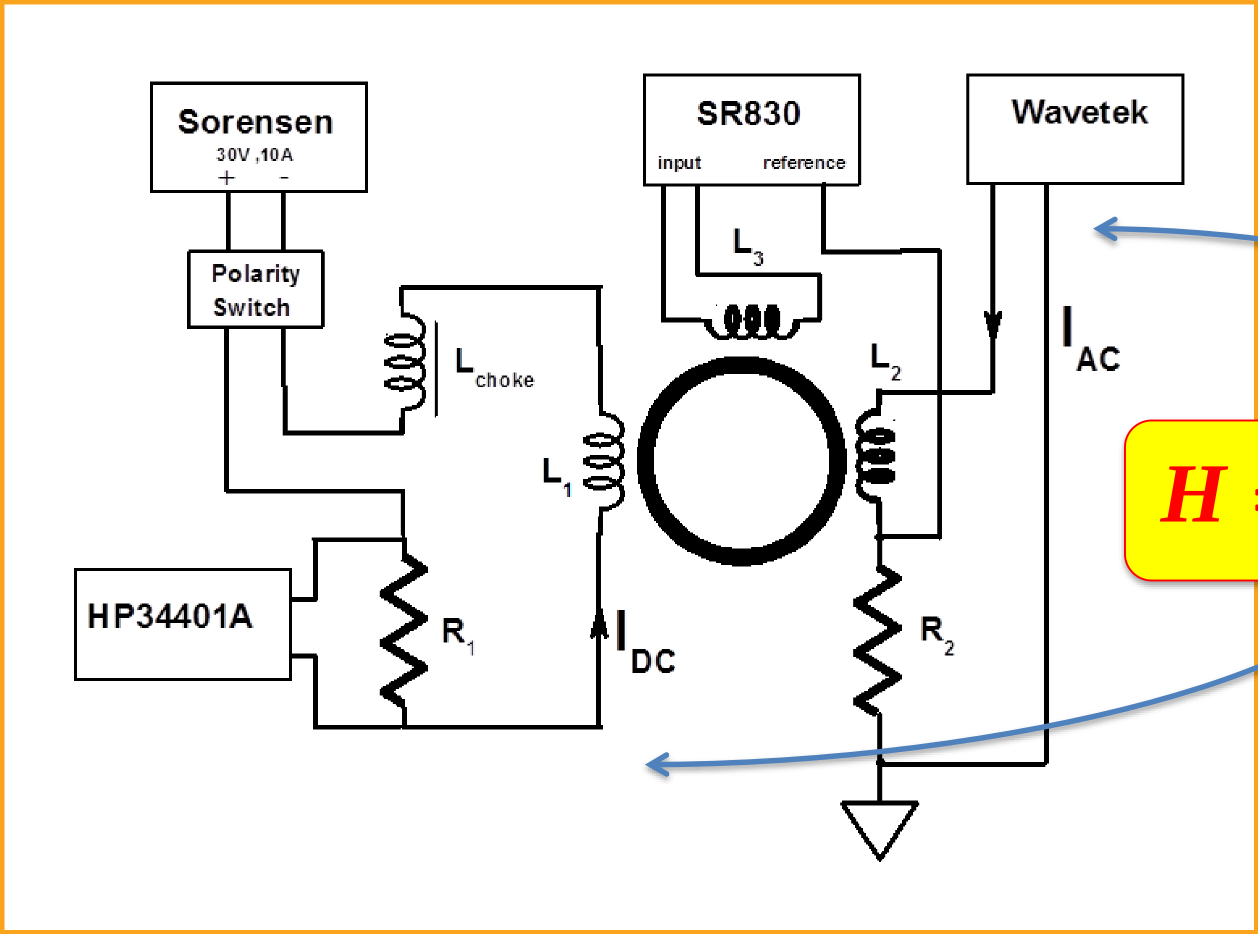
By applying a small modulation of the H field we can measure the derivative of the B-H hysteresis loop or dependence of the magnetic permeability on H field

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

Setup #1. Investigation of the hysteresis loops.



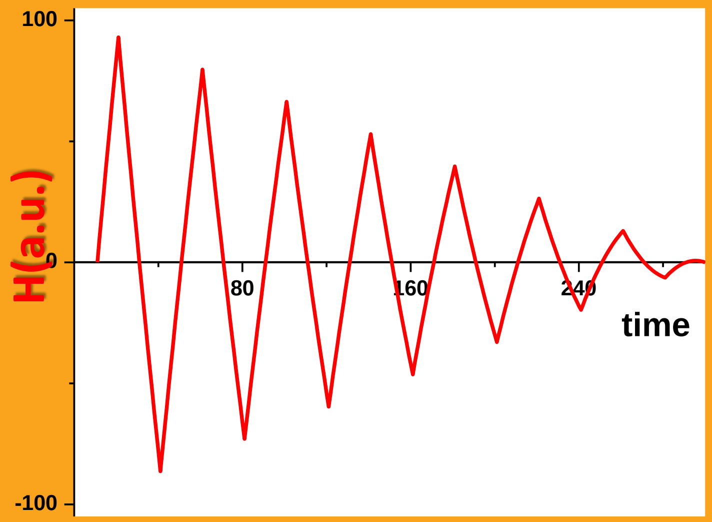
Setup #1. Investigation of the hysteresis loops.



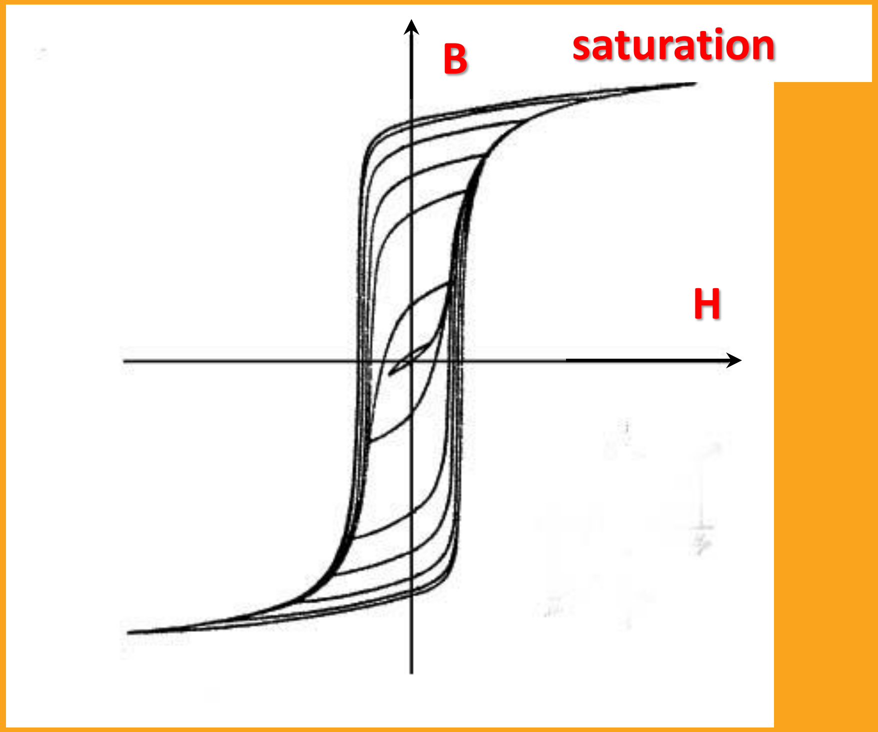
$$H = \frac{N_p I_p}{2\pi r}$$

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

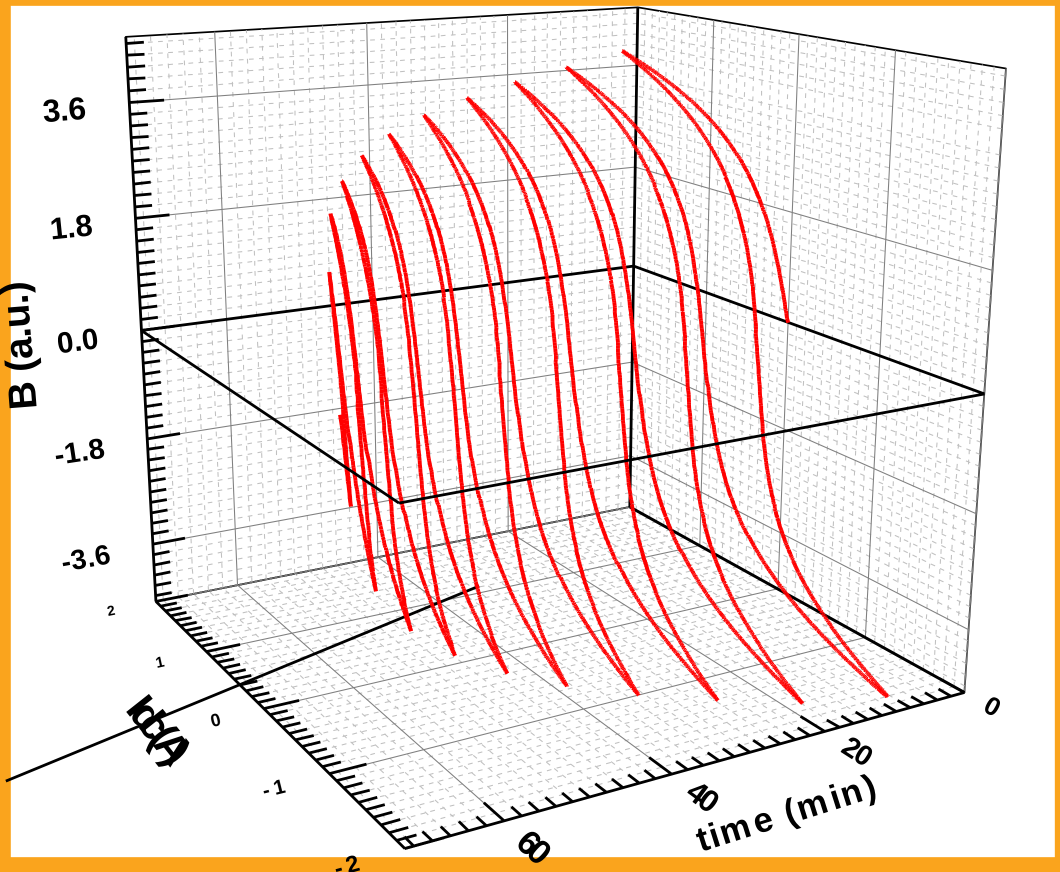
Major/minor loops. Demagnetization



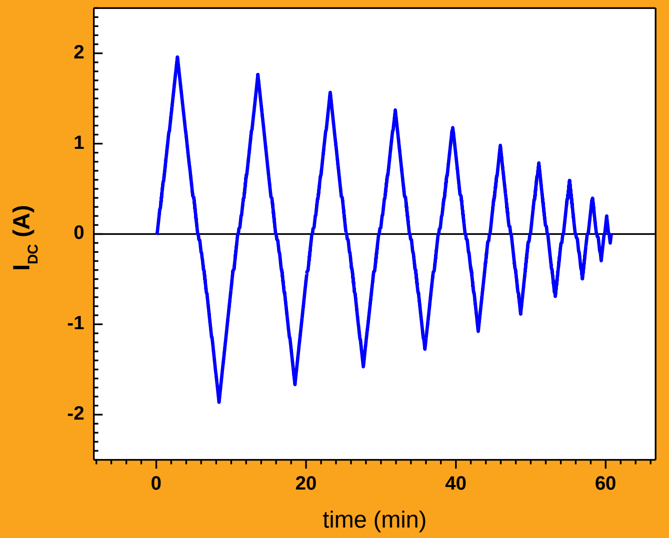
Waveform of H-field



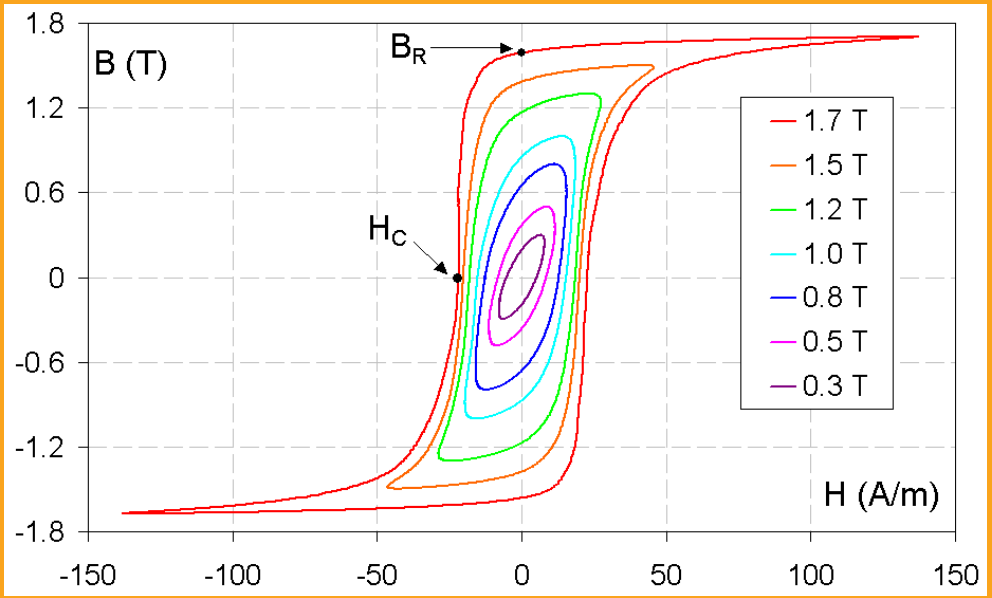
Demagnetization



Demagnetization of 4C65 toroid from Ferroxcube



Hysteresis Loops



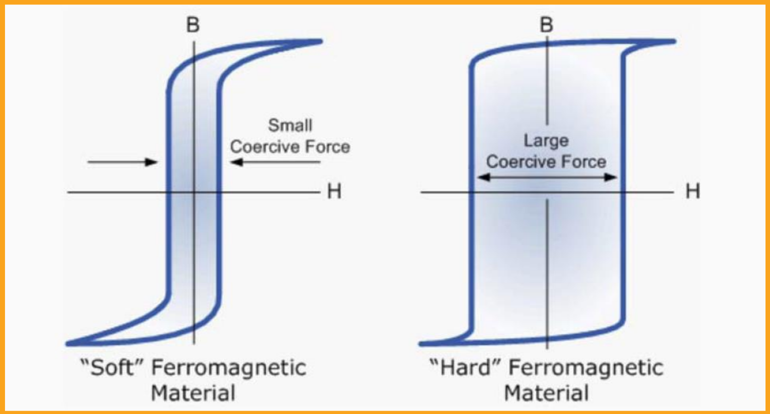
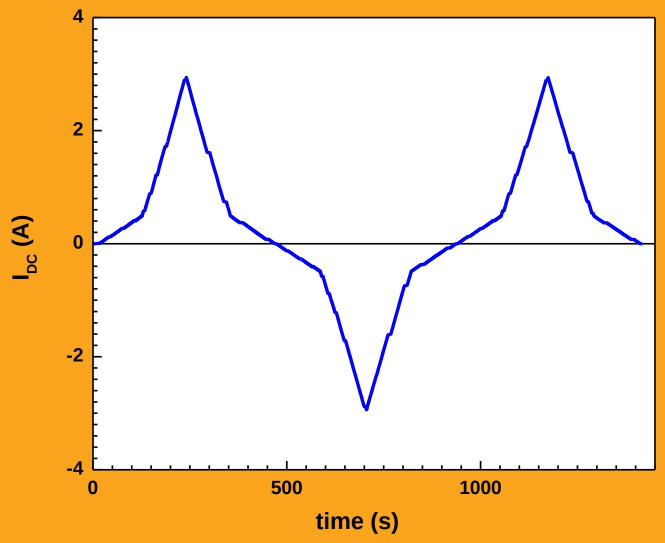
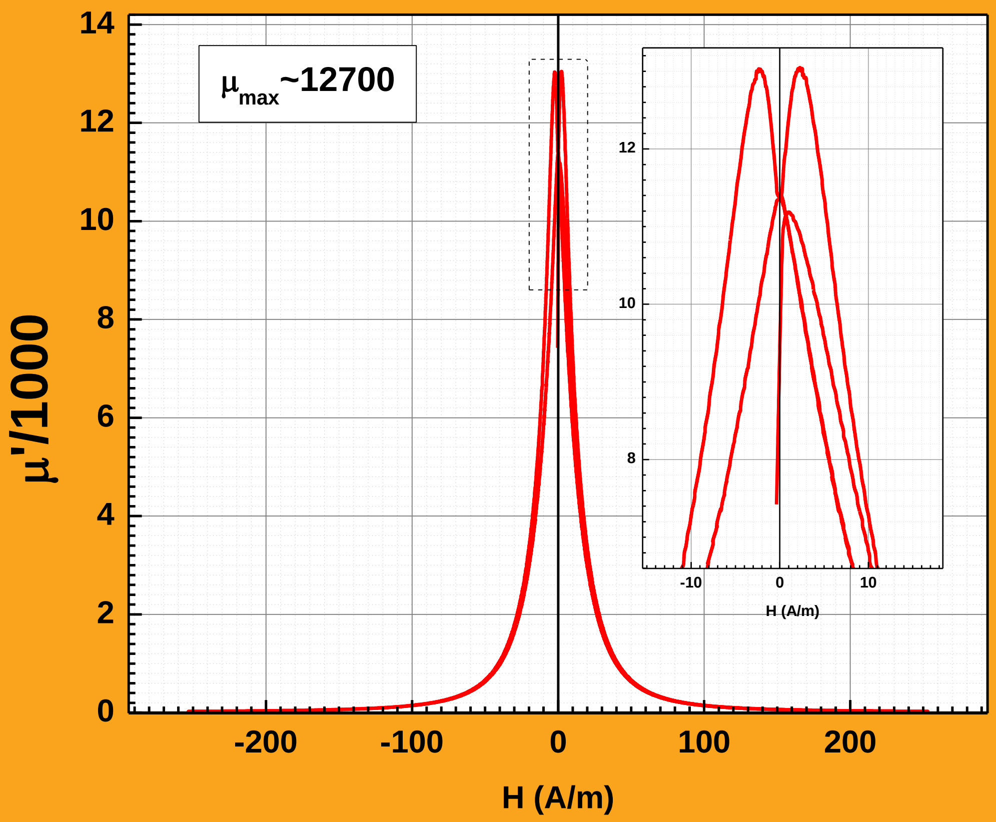


Fig. A family of AC hysteresis loops for grain-oriented electrical steel (B_R denotes *remanence* and H_C is the *coercivity*). Courtesy Zureks (Wikipedia)

Measuring the magnetic permeability



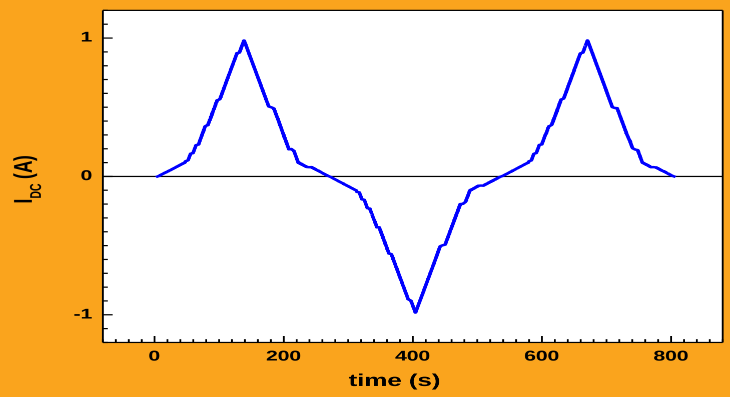


DC current profile and magnetic permeability of Magnetics ZW44715TC

From permeability to B-H hysteresis loop

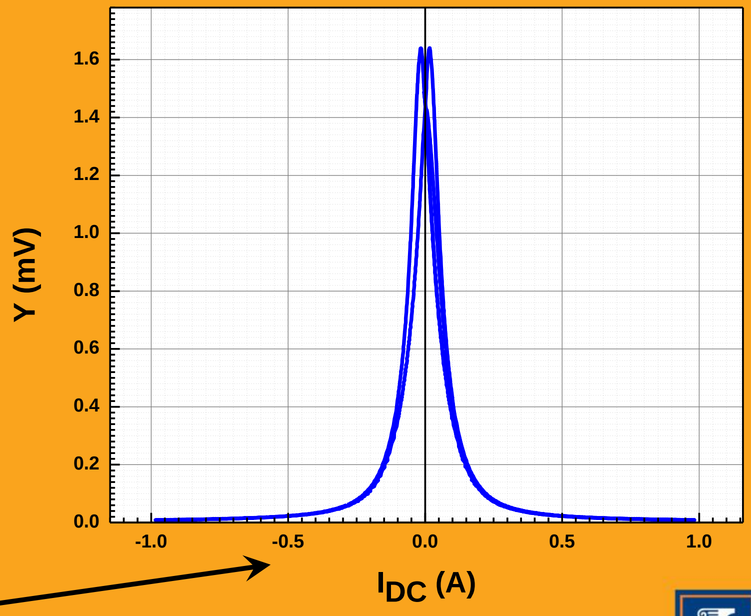
Step#1. Performing one fast IDC scan the based on the result preparing the "smart" IDC profile

ECE storeroom unknown material Sample #5



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

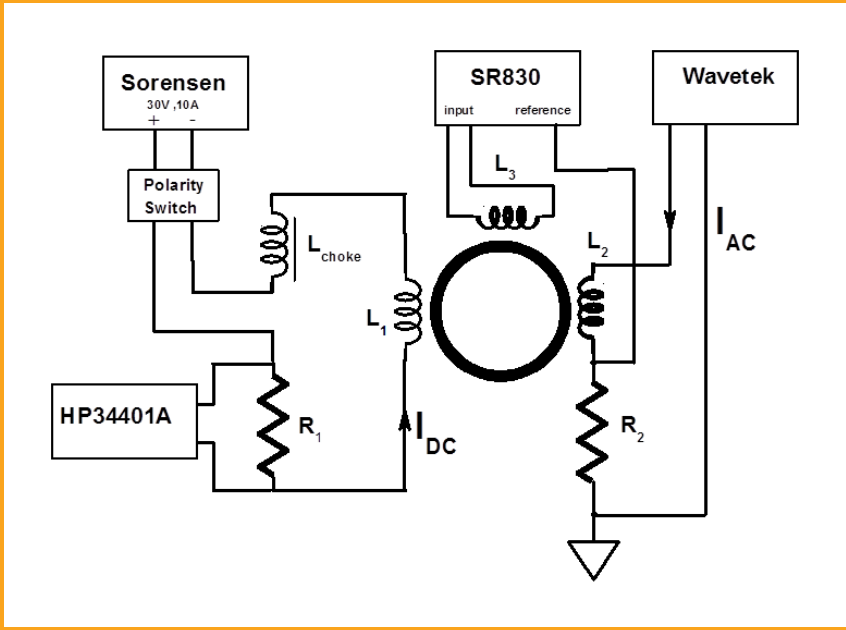
Voltage units measured by SR830



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

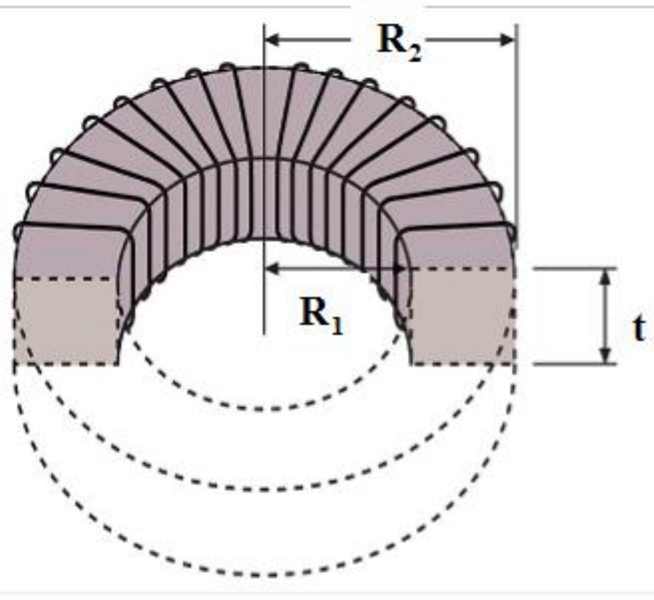
$$V_{lock-in} = -\frac{d\Phi}{dt};\Phi = \vec{B} \bullet \vec{S}$$

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 $d\Phi$



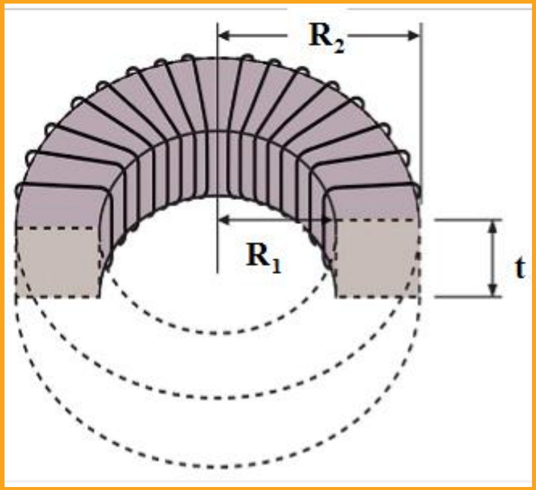
For toroid: $H = \frac{N_p I_p}{2\pi r}$

$R_2 < r < R_1$

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

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

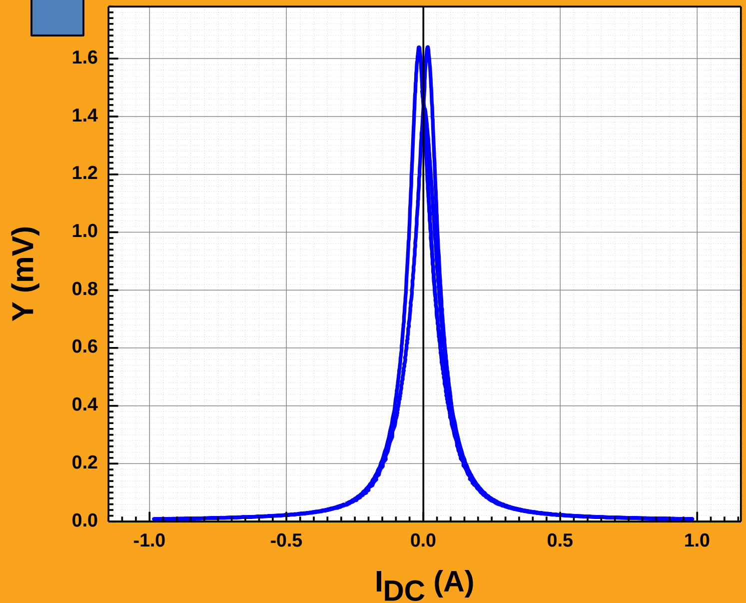
Inductance of the toroid:

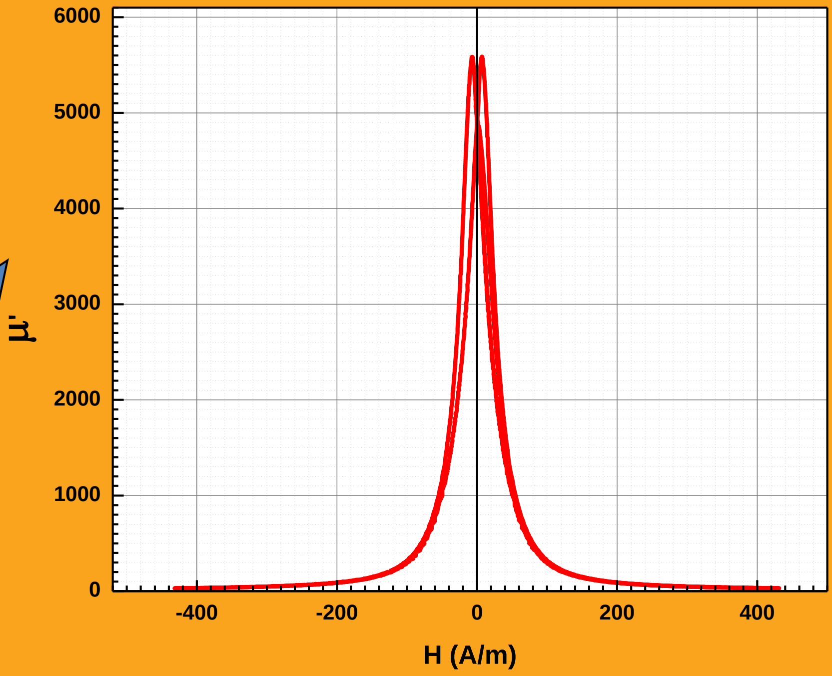
$$L = \frac{\Phi}{I}; \quad L = \mu_r L_0 = (\mu' - i\mu'') L_0$$

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

From permeability to B-H hysteresis loop

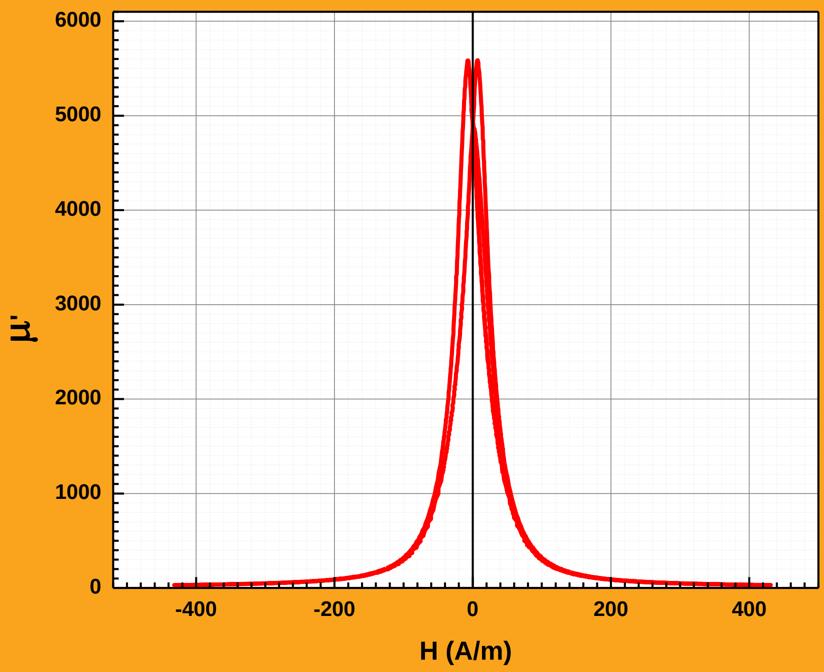
$$V_{lock-in} = \mu_r L_0 \frac{dI_p}{dt}$$





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

From permeability to B-H hysteresis loop

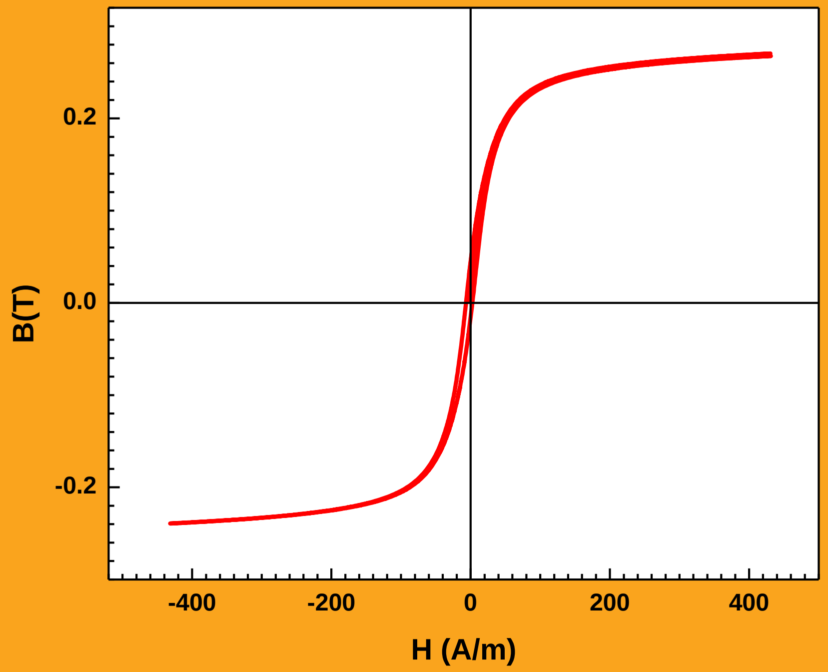


Step#4. From μ_r(H) to B-H

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

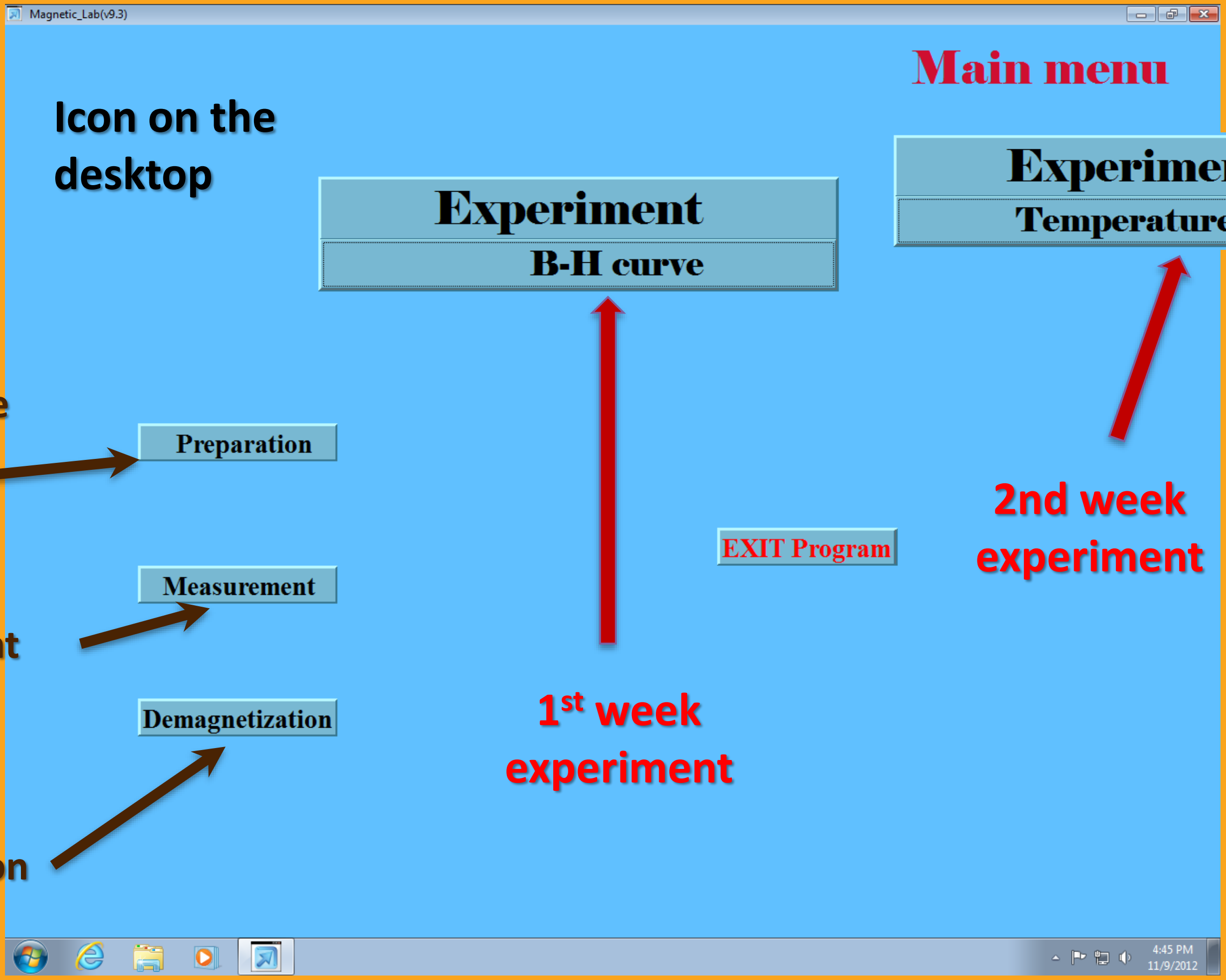
After integrating →

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



Software issue

Magnetic Lab v9.2



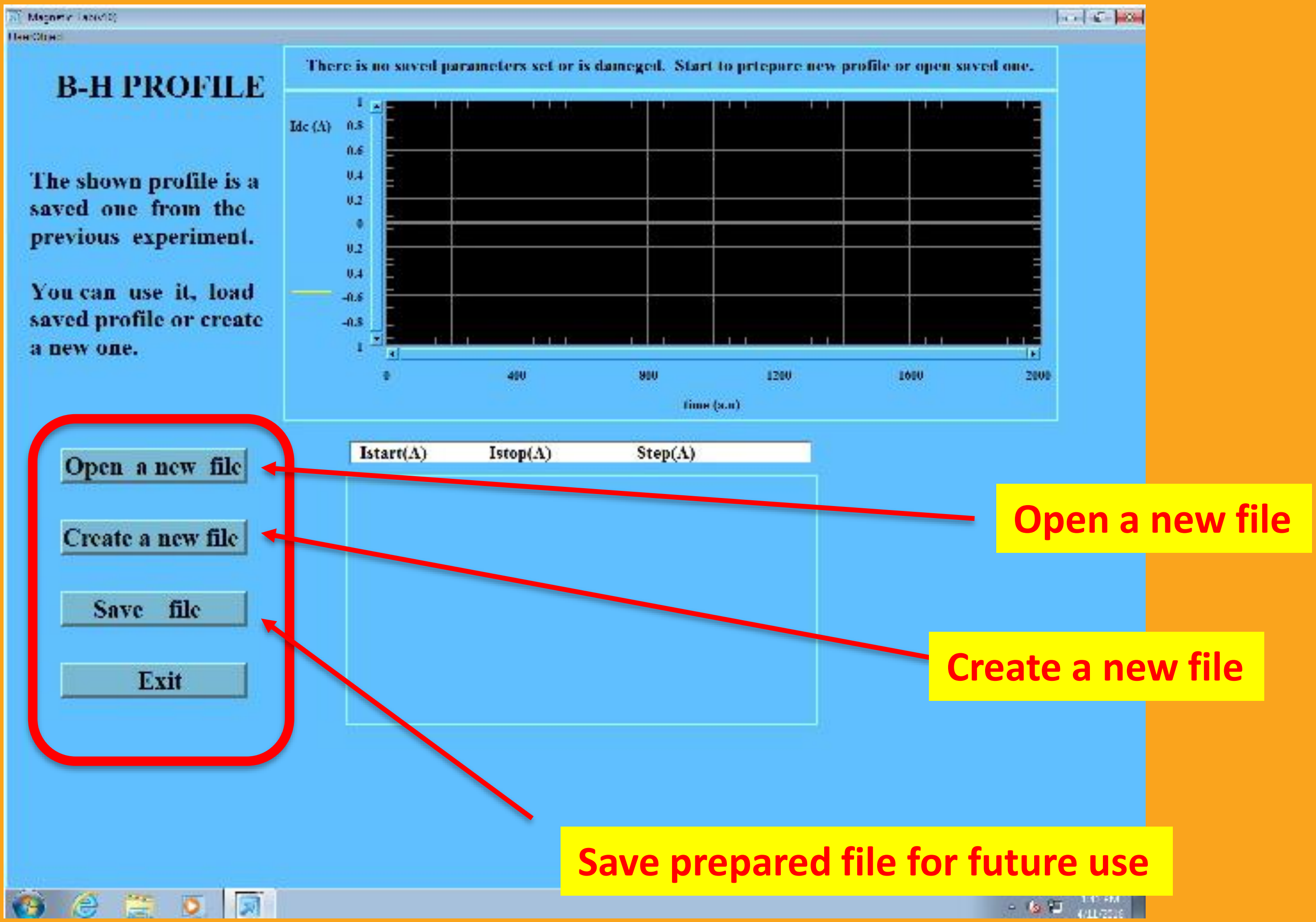
Preparation of the profile of the experiment

B-H measurement

Demagnetization

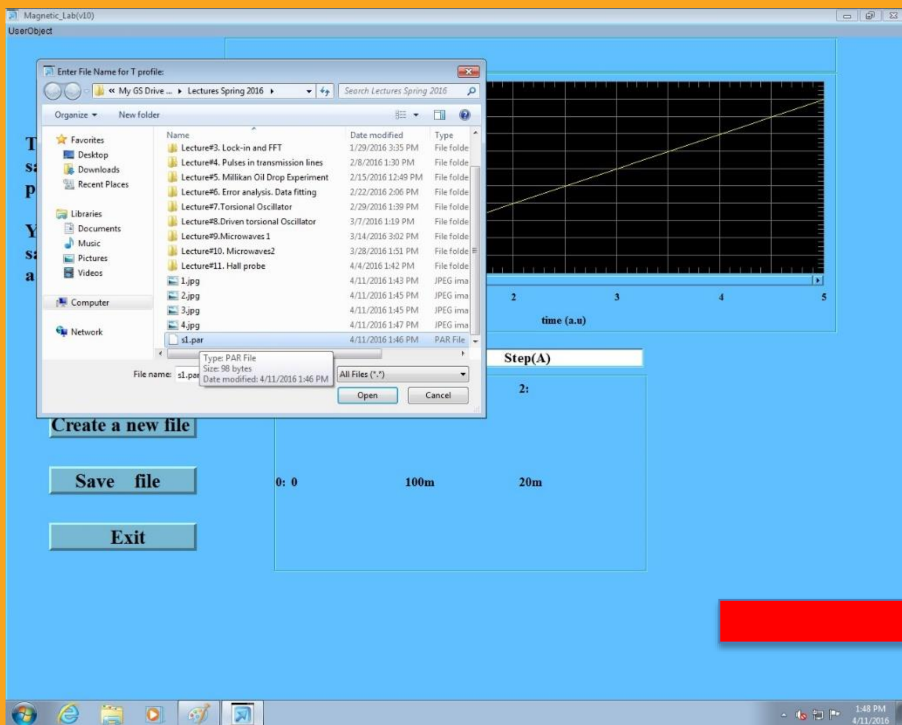
Software issue

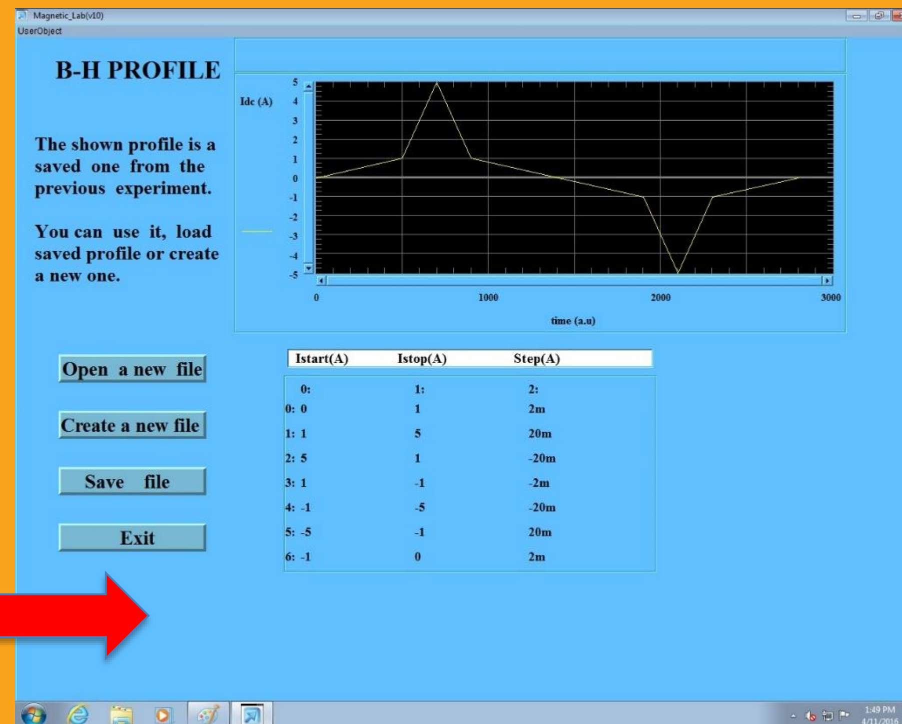
Measuring profile preparation. Using profile template



Software issue

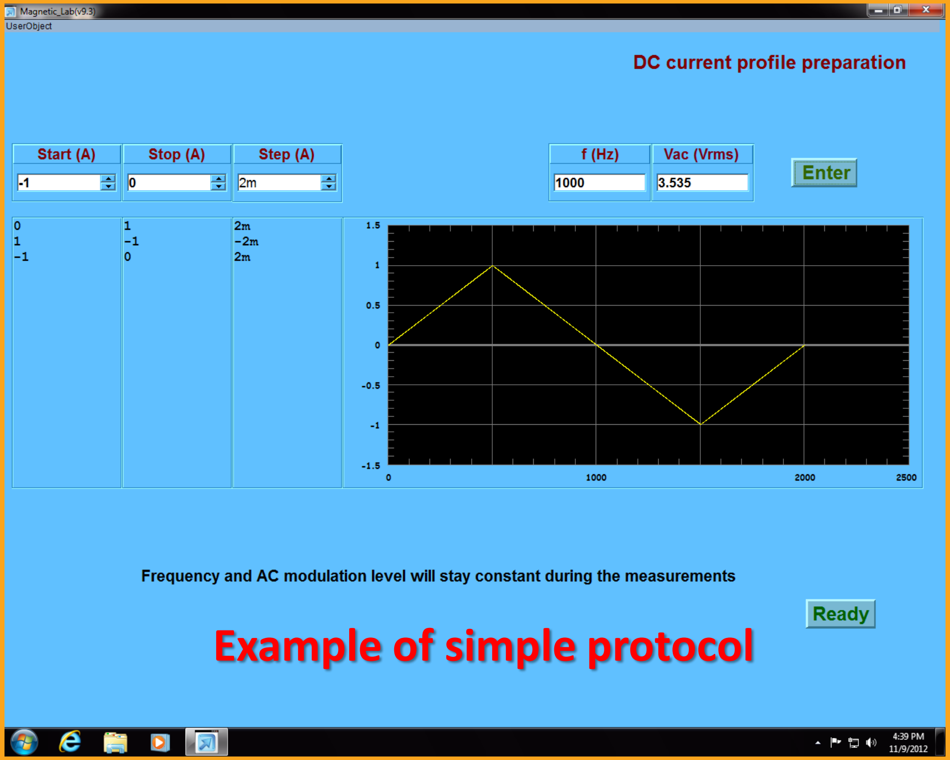
Measuring profile preparation. Using profile template.



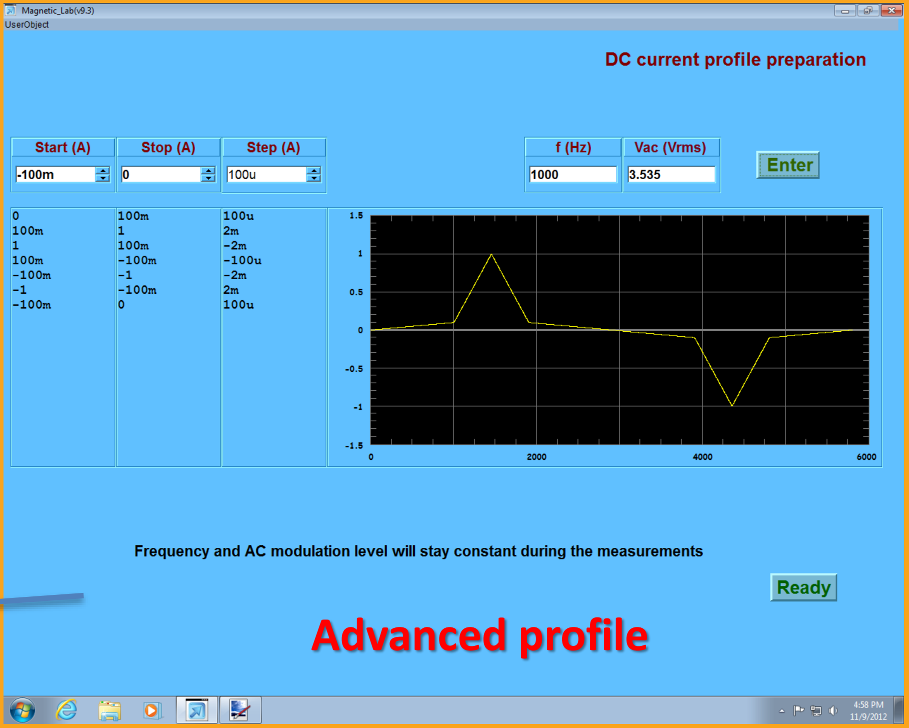


Software issue

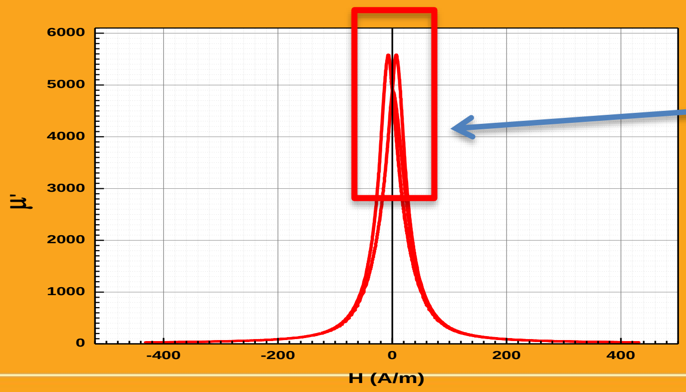
Measuring profile preparation



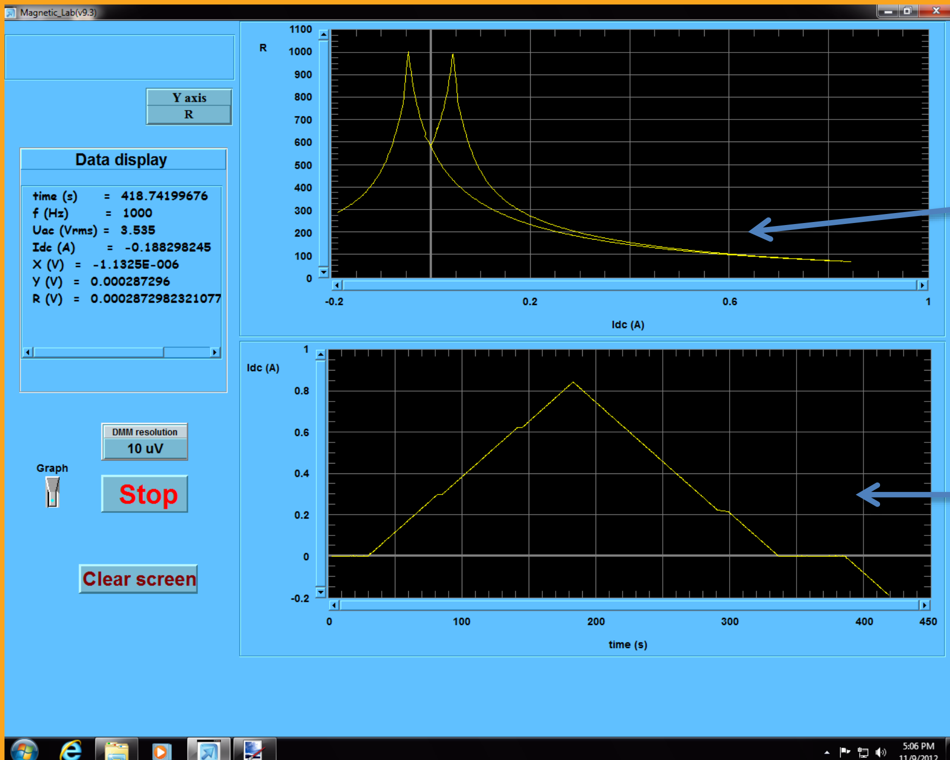
Example of simple protocol



Advanced profile



Software issue



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	-1.22025E-	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.otw

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-6	7.72332E-5	7.72421E-5	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-5	h(m)	0.00825	3.35179E-7	51.55108	0.76061	0.01335
4	13.578	1000	3.535	0.00988	-1.03564E-6	7.65999E-5	7.66069E-5	r2	22.35	3.35179E-7	51.44604	0.69556	0.01756
5	13.938	1000	3.535	0.01205	-1.15485E-6	7.62646E-5	7.62733E-5	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

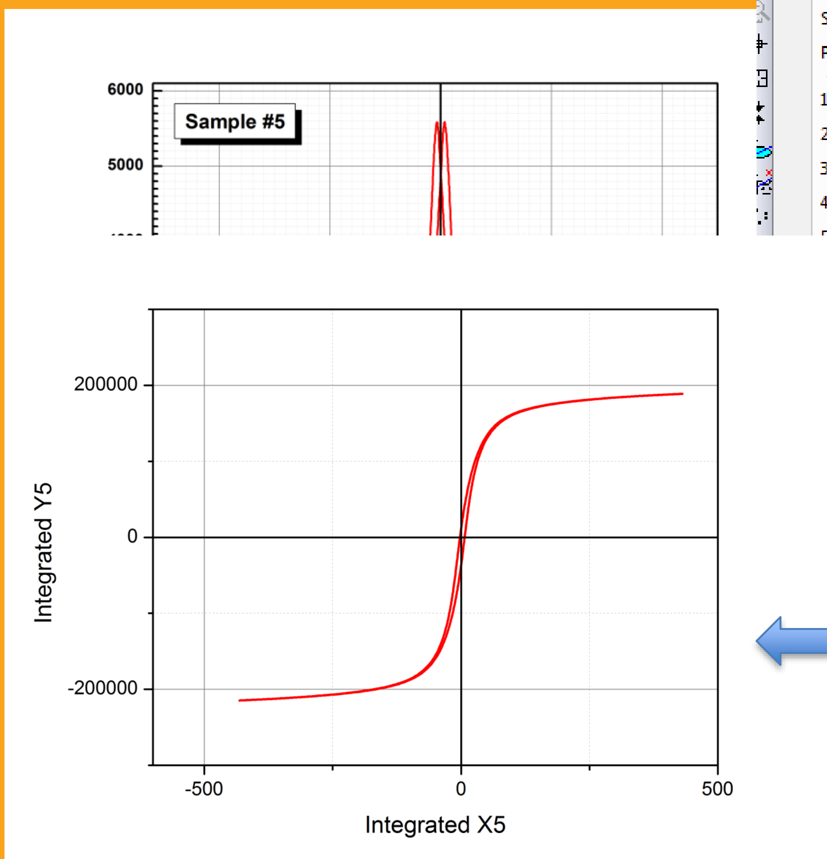
Raw data

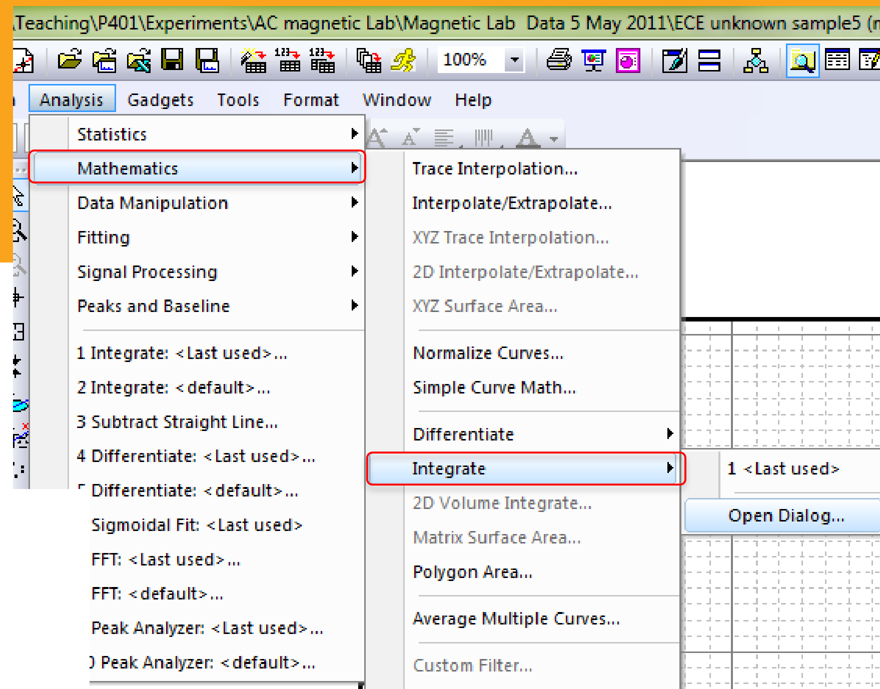
Parameters

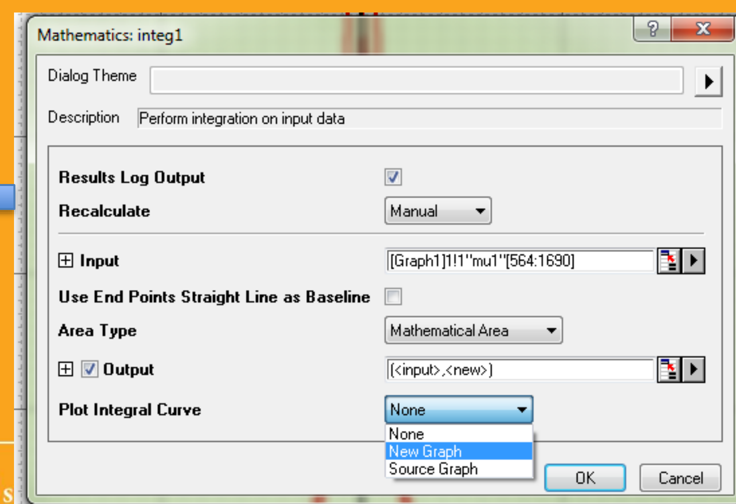
Calculated results

Data analysis using Origin. Integrating.

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

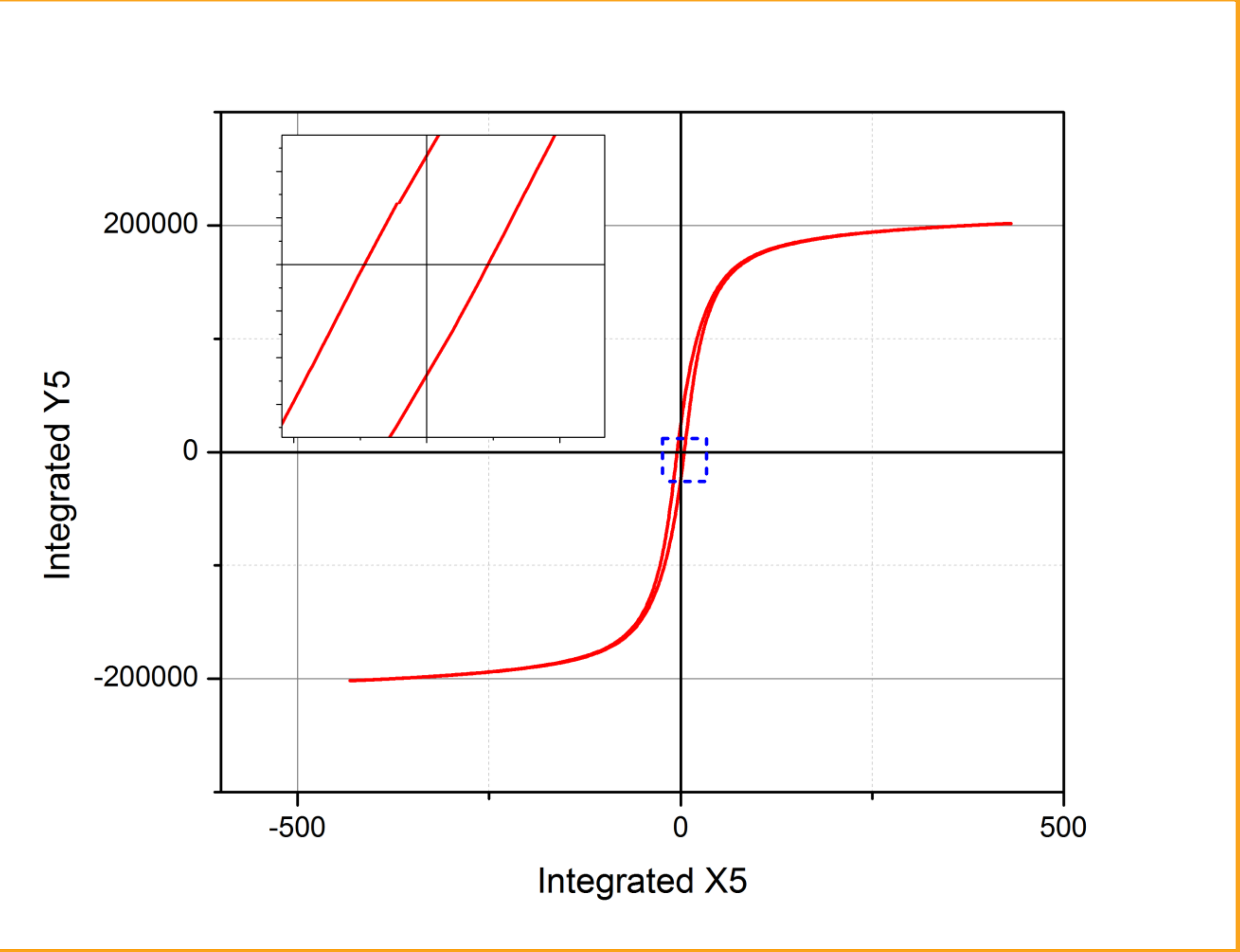






Data analysis using Origin. Integrating.

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



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**