UNIVERSITY OF ILLINOIS
AT URBANA-CHAMPAIGN

AC Measurement of Magnetic Susceptibility

Physics 401, Spring 2017
Eugene V. Colla

Outline

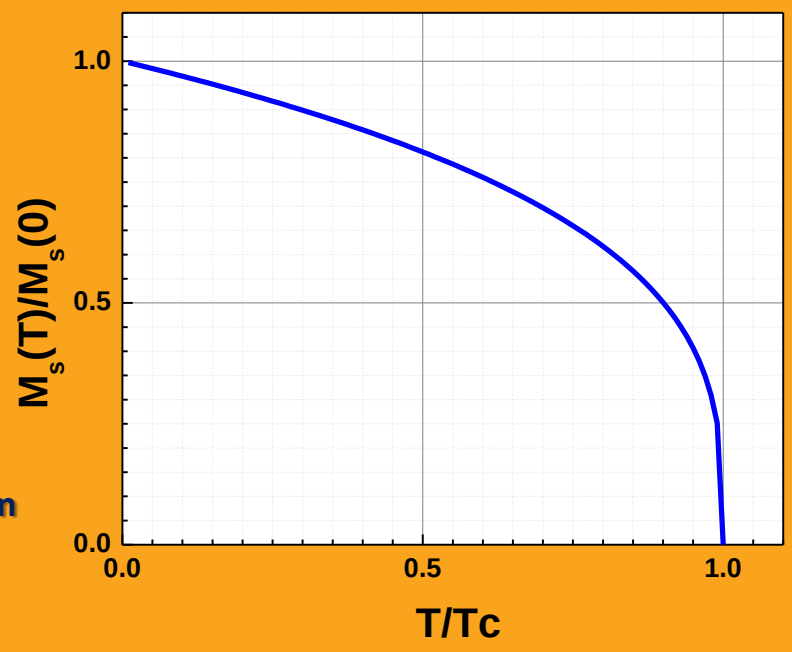
- Ferromagnetism
- Measurement of the magnetic properties of the materials
- Lab experimental setup and experiments
- Some results

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.

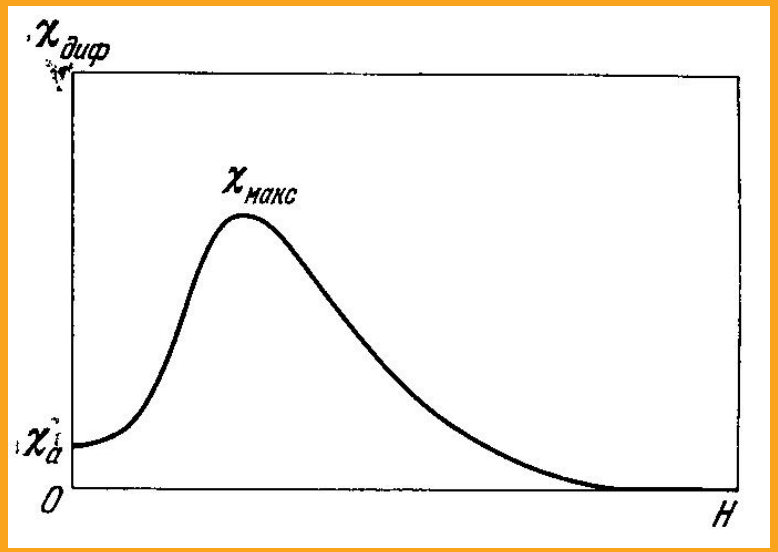
The main parameter of the ferromagnetic phase transition is spontaneous magnetization



Typical behavior of spontaneous magnetization as function of temperature

Ferromagnetic materials.

Aleksandr Stoletov
(1839 –1896)



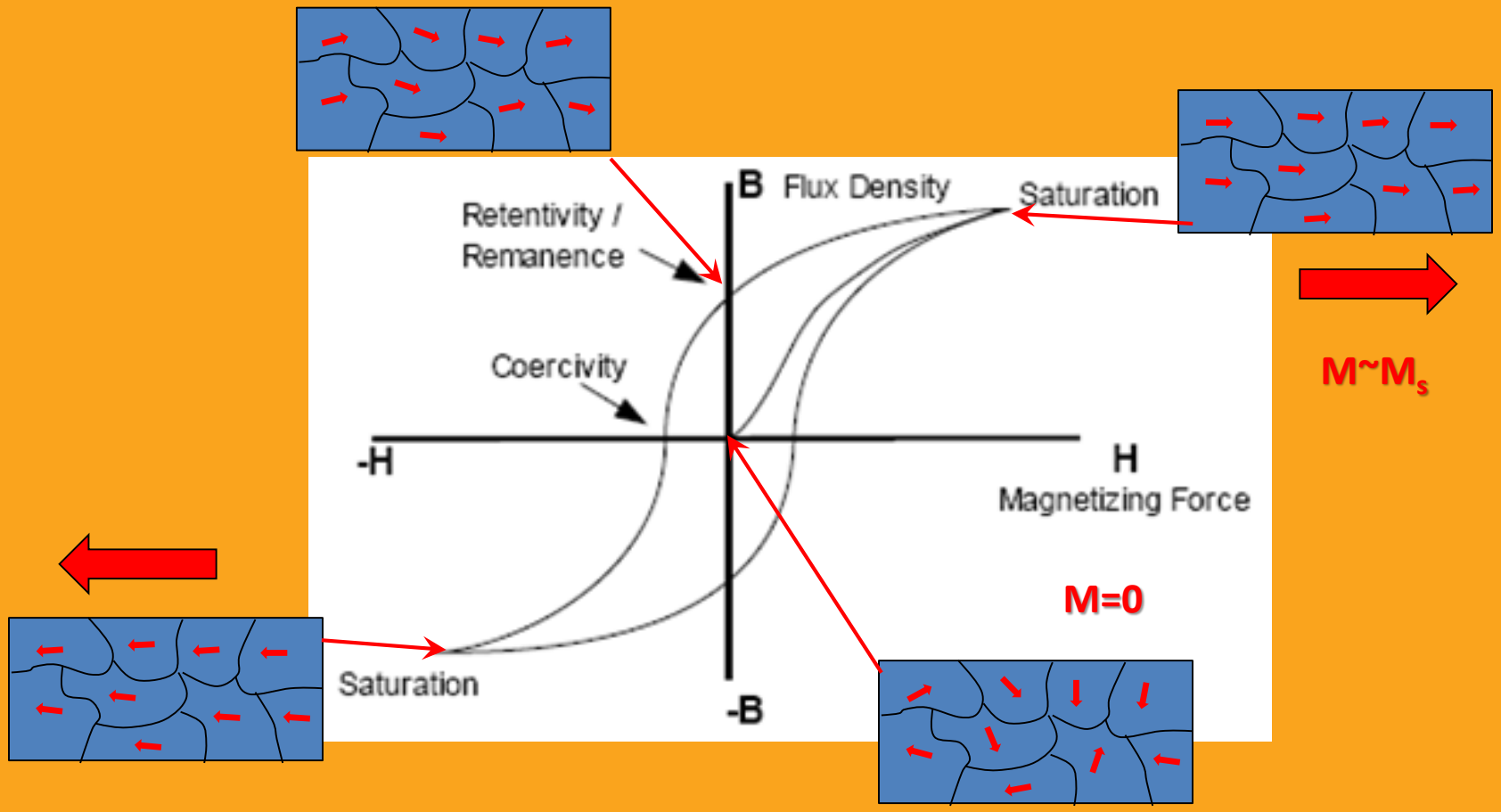
"Stoletov" curve

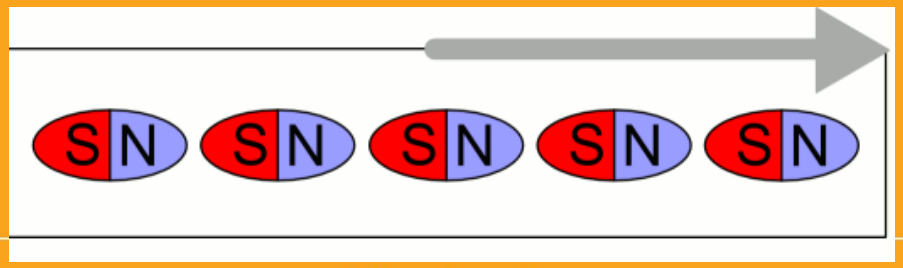
$$\chi = \frac{dM}{dH}$$

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.

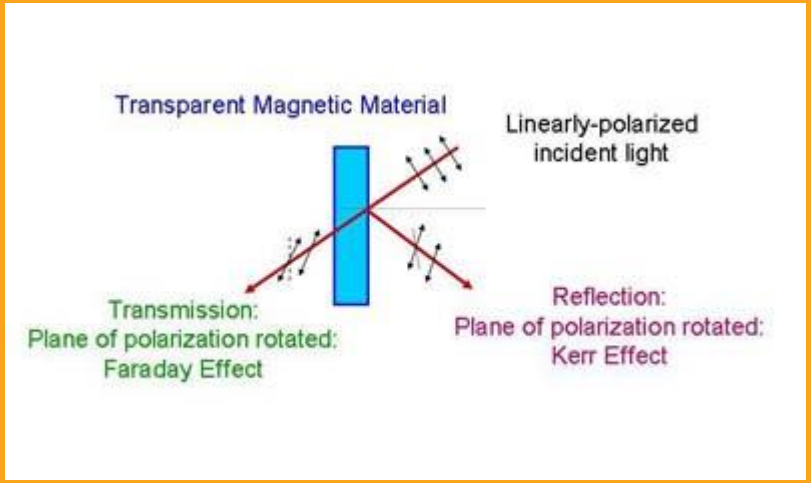
Domains. Hysteresis loop.



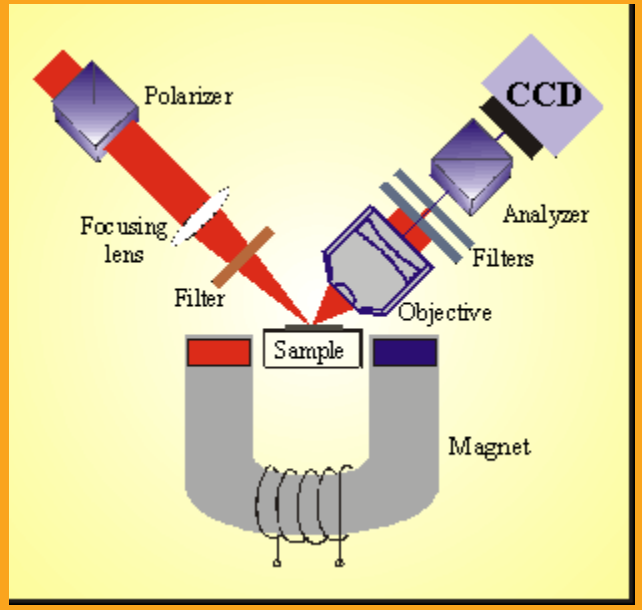


* Courtesy Wikipedia

Kerr Effect. Visualization of the Domains



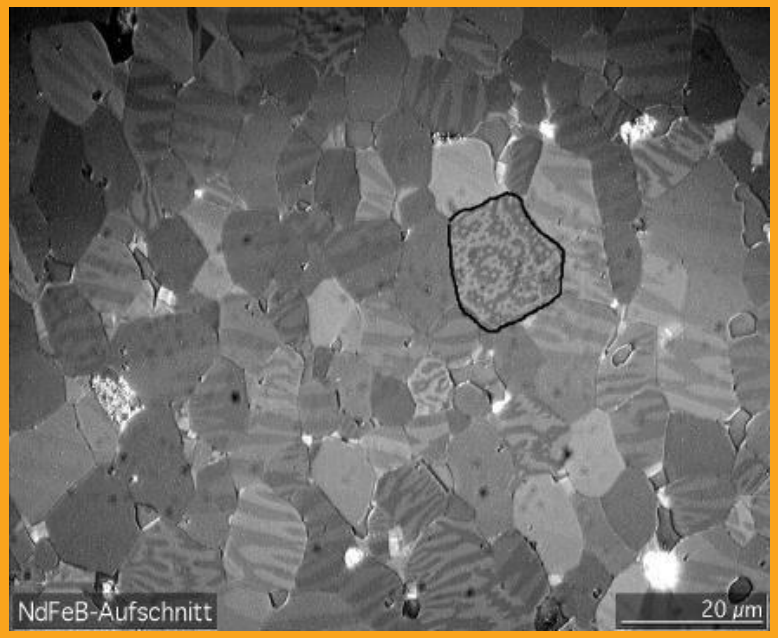
John Kerr
17 Dec 1824 – 15 Aug 1907



The Diagram of Typical Kerr Microscope

Courtesy of Radboud University, Nijmegen
The Netherlands

Domains

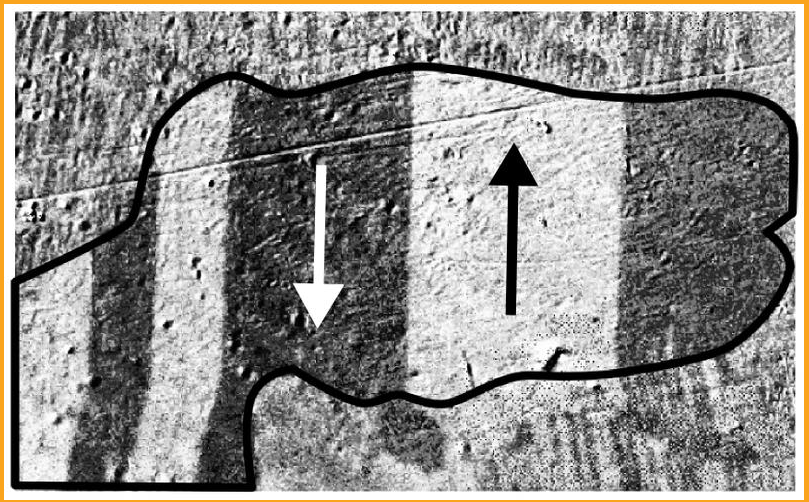


Several grains of NdFeB with magnetic domains made visible via contrast with a Kerr microscope.

Courtesy of Wikipedia

Kerr microscope
Courtesy of University of Uppsala (Sweden)

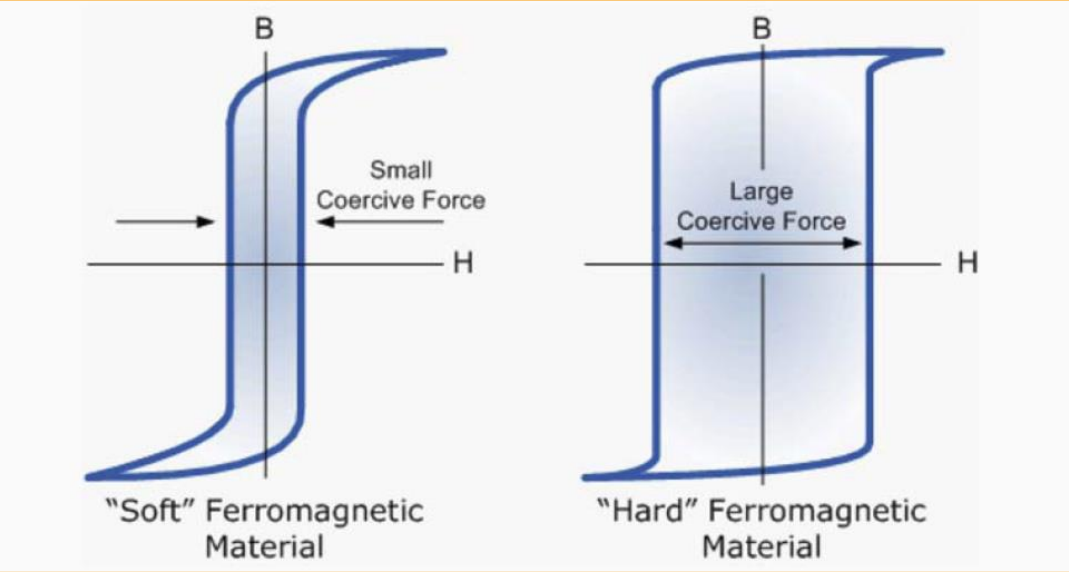
Domains



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

Courtesy of Wikipedia

Hysteresis Loops. Remagnetization loses



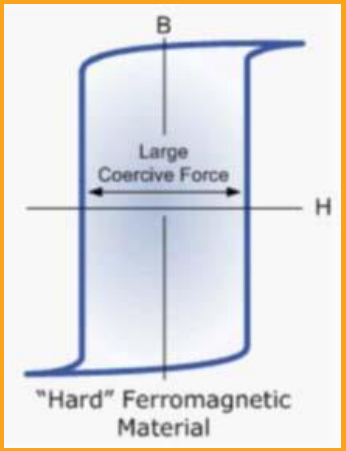
Energy of the magnetic field

$$W = V \int HdB$$

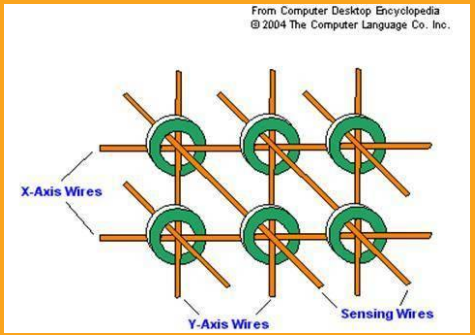
By cycling around the loop

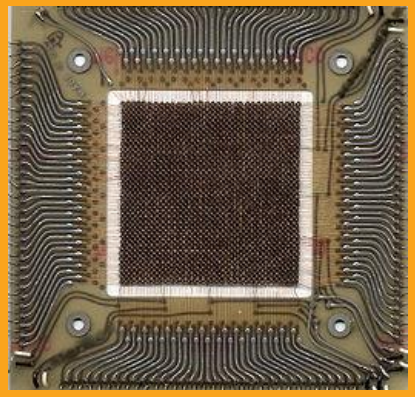
$$W_{loop} = V \oint HdB = V*Loop\_area$$

“Hard” materials. Application.



RAM memory

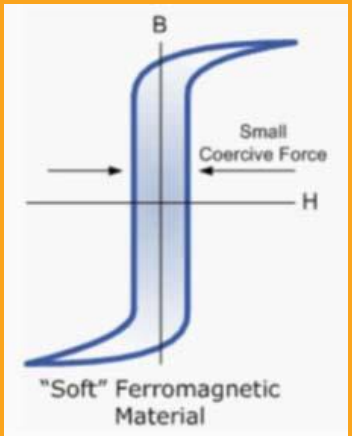




Permanent magnets

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)

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

$$\mu_r = 1 + \chi$$

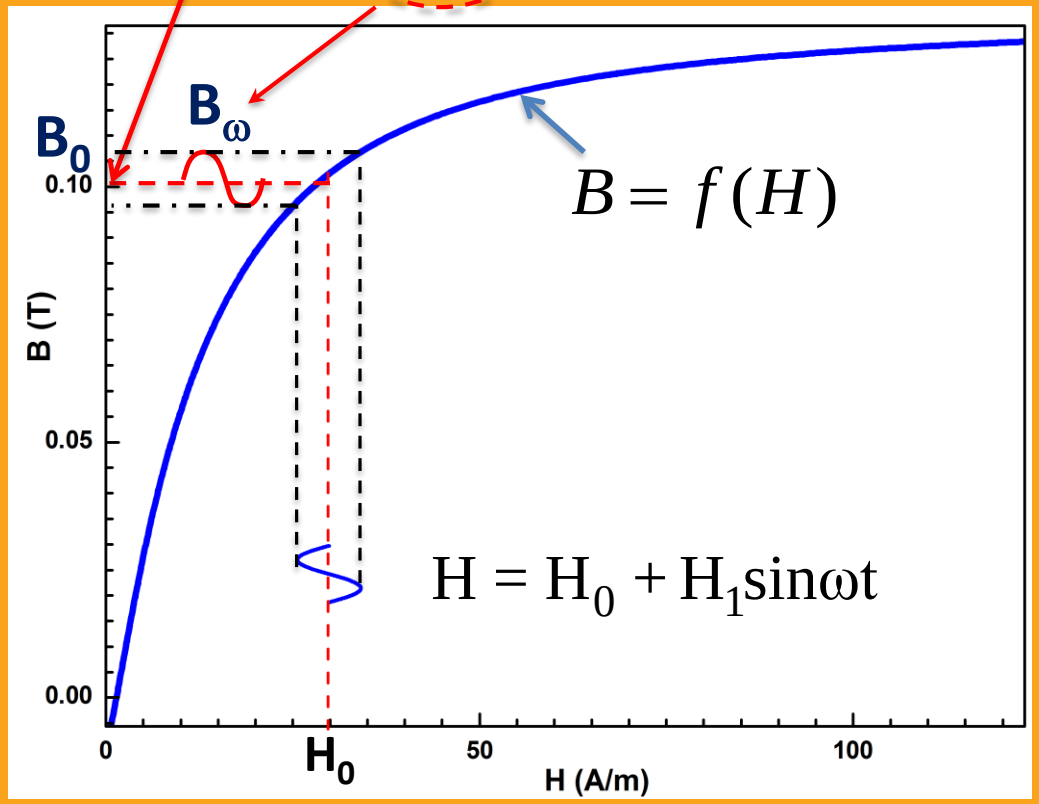
$$\mu = \mu_0 \mu_r = \frac{dB}{dH}; \quad \mu_r = \frac{1}{\mu_0} \frac{dB}{dH}$$

Modulation Spectroscopy

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

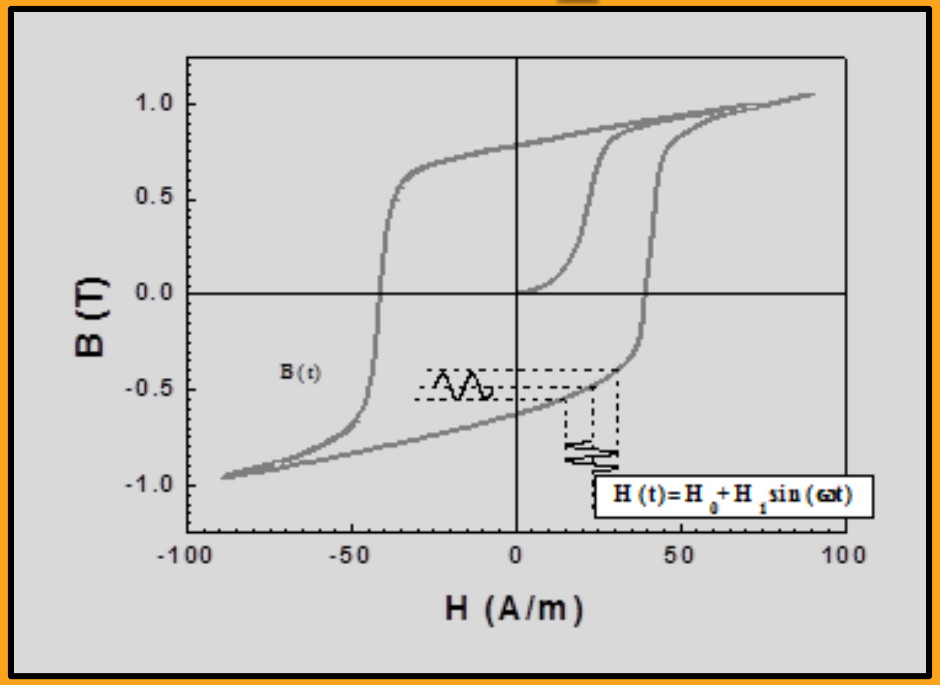
$$B = f(H_0) + \frac{df}{dH}(H_1 \sin\omega t) + \ldots$$

H_1=const



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

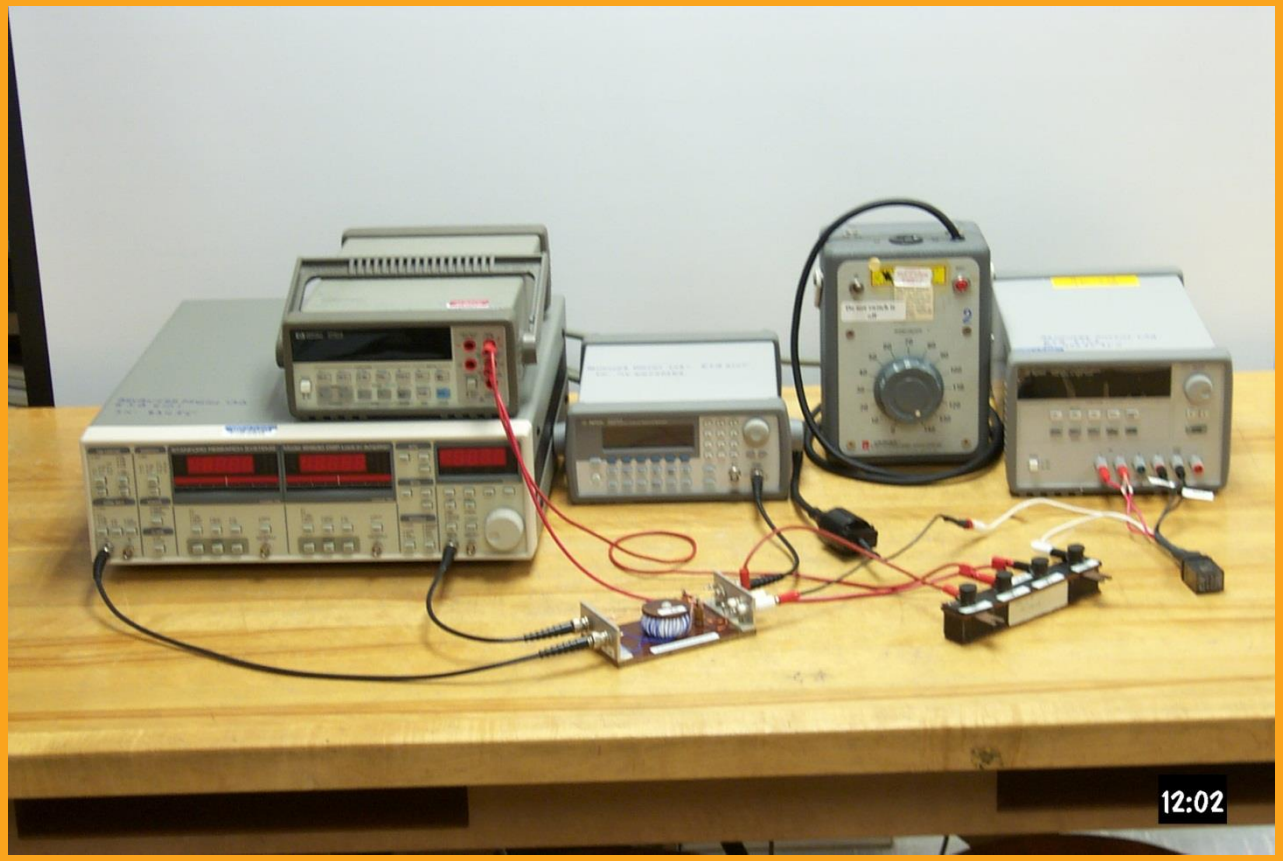
Measuring the magnetic permeability



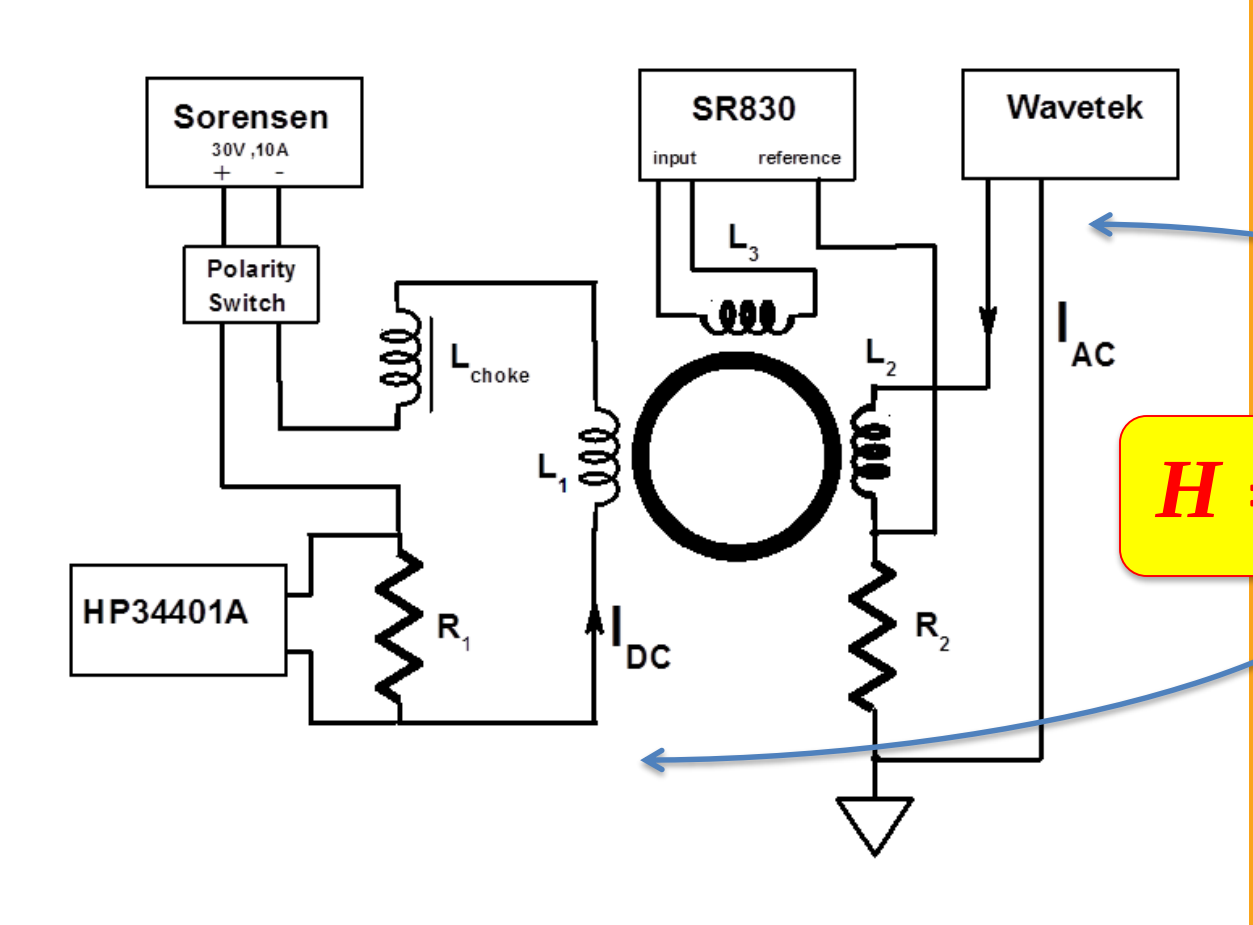
By applying a small modulation of the H field we can measure the derivative of the B-H hysteresis loop or dependence of the magnetic permeability on H field

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

Setup #1. Investigation of the hysteresis loops.



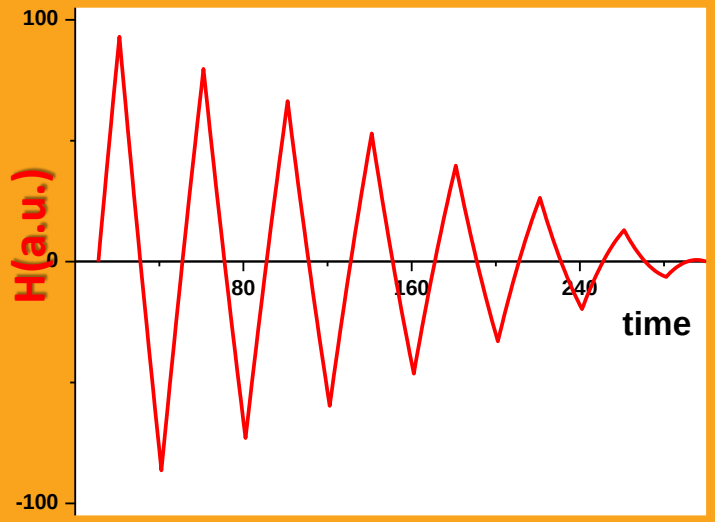
Setup #1. Investigation of the hysteresis loops.



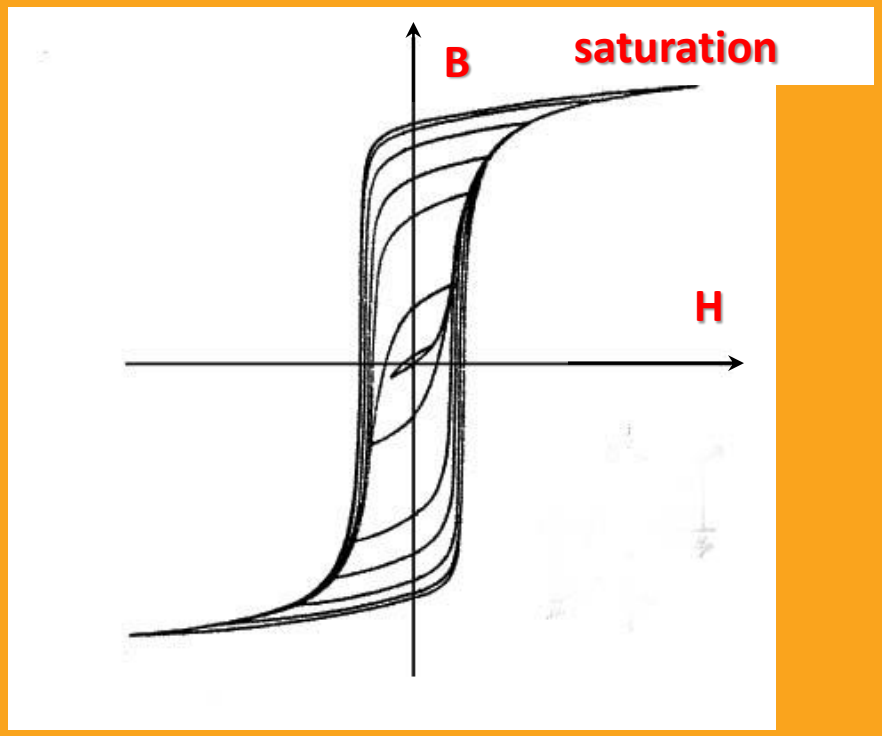
$$H = \frac{N_p I_p}{2\pi r}$$

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

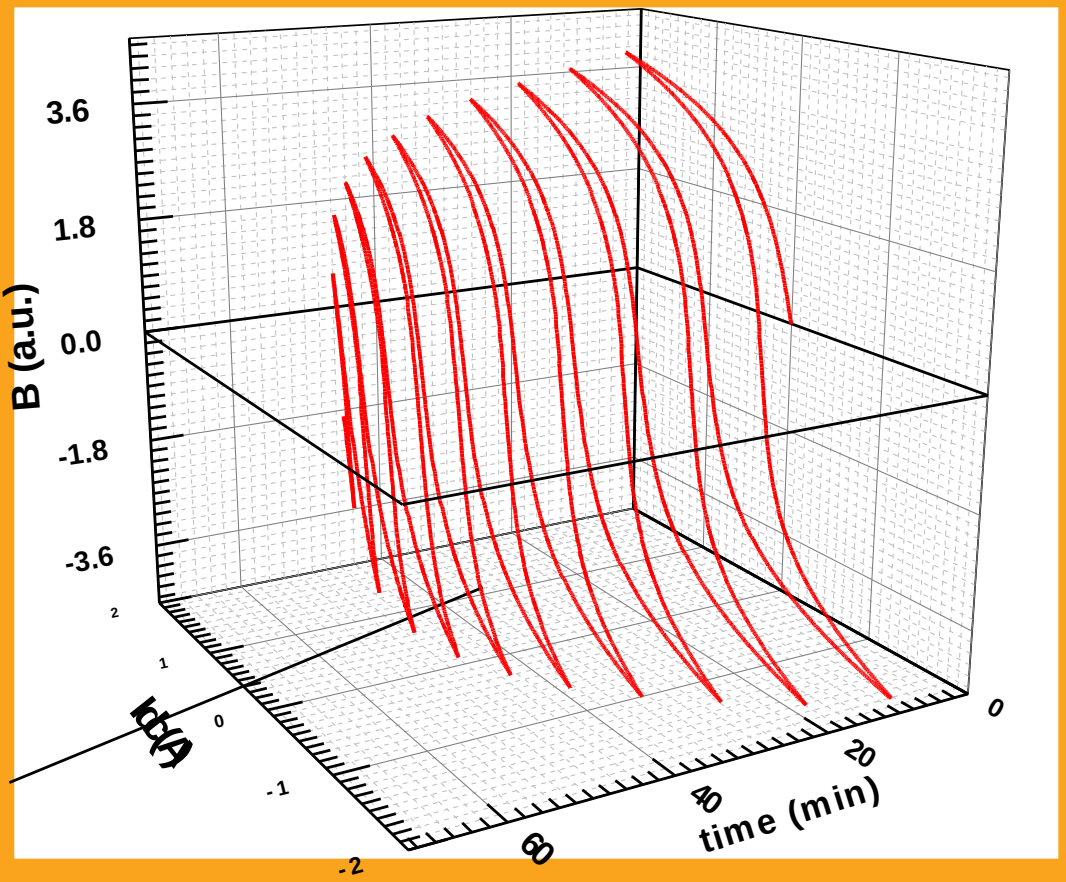
Major/minor loops. Demagnetization



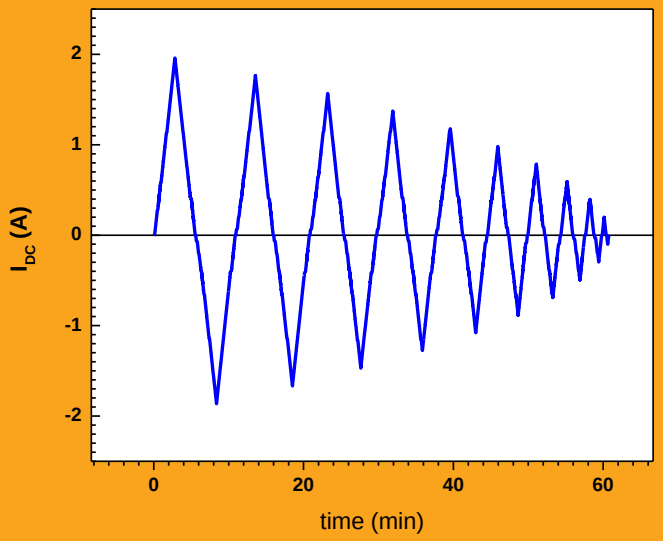
Waveform of H-field



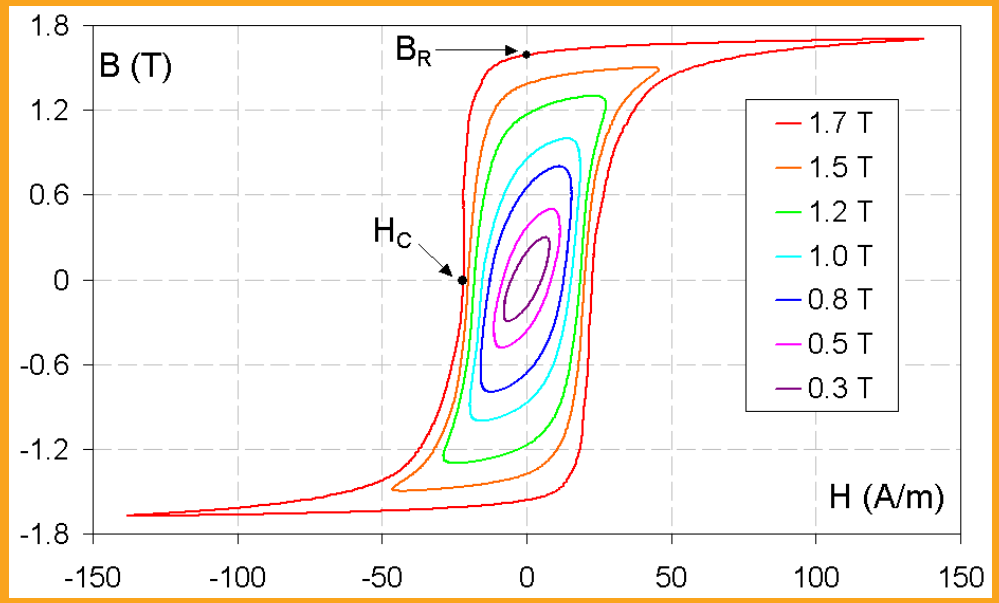
Demagnetization



Demagnetization of 4C65 toroid from Ferroxcube



Hysteresis Loops



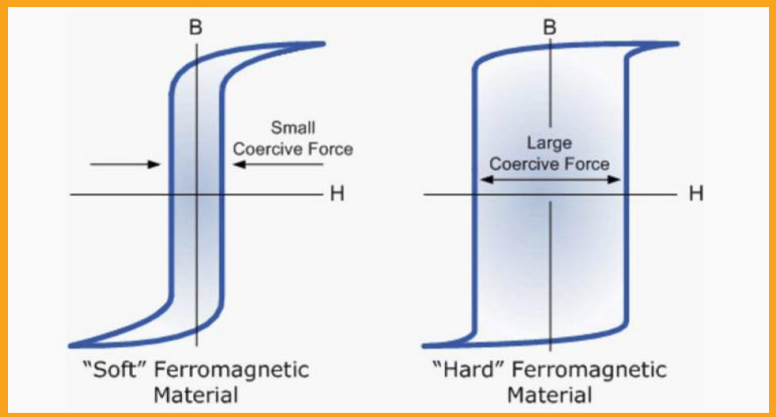
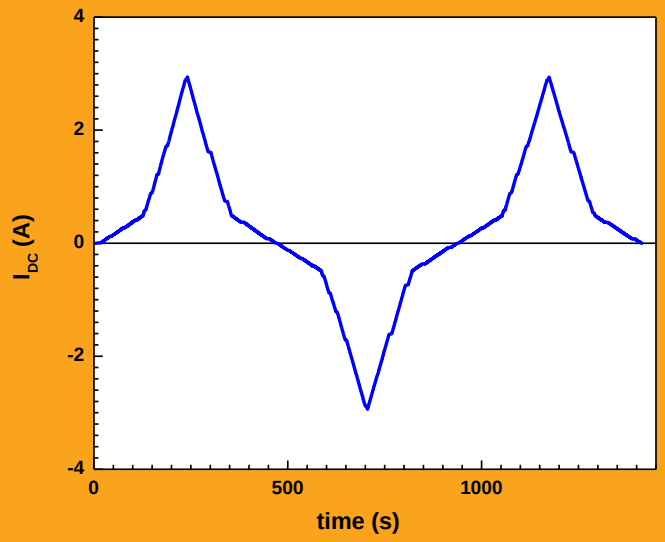
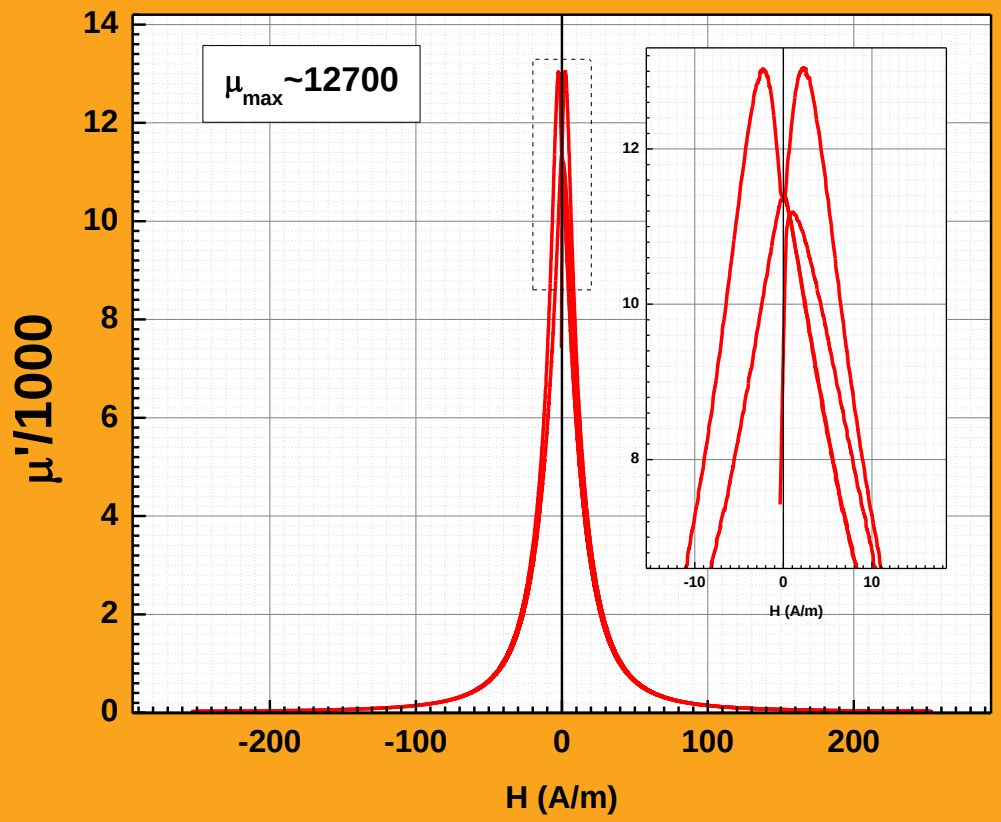


Fig. A family of AC hysteresis loops for grain-oriented electrical steel (B_R denotes *remanence* and H_C is the *coercivity*). Courtesy Zureks (Wikipedia)

Measuring the magnetic permeability



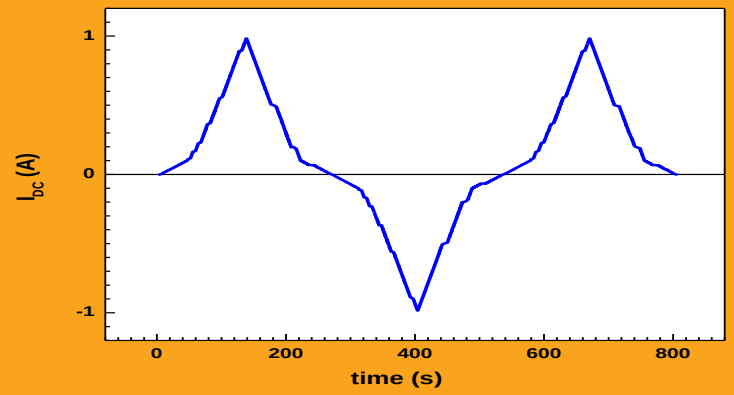


DC current profile and magnetic permeability of Magnetics ZW44715TC

From permeability to B-H hysteresis loop

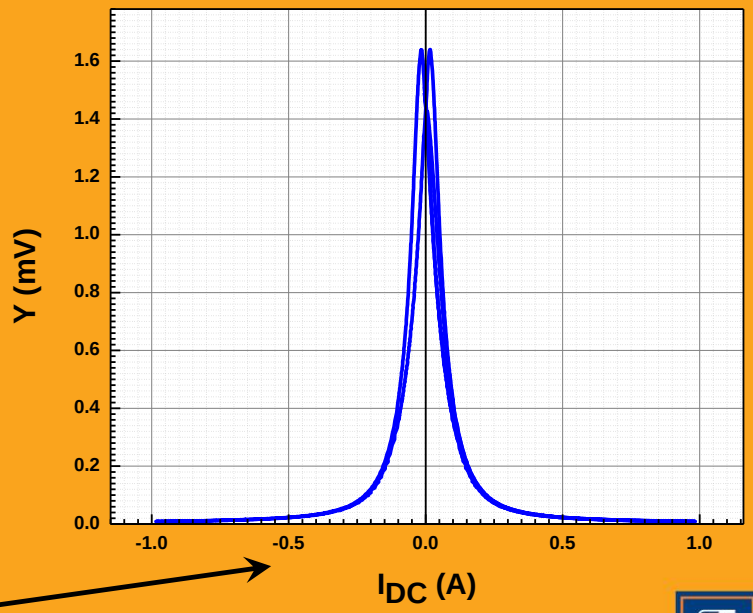
Step#1. Performing one fast IDC scan the based on the result preparing the "smart" IDC profile

ECE storeroom unknown material Sample #5



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

Voltage units measured by SR830



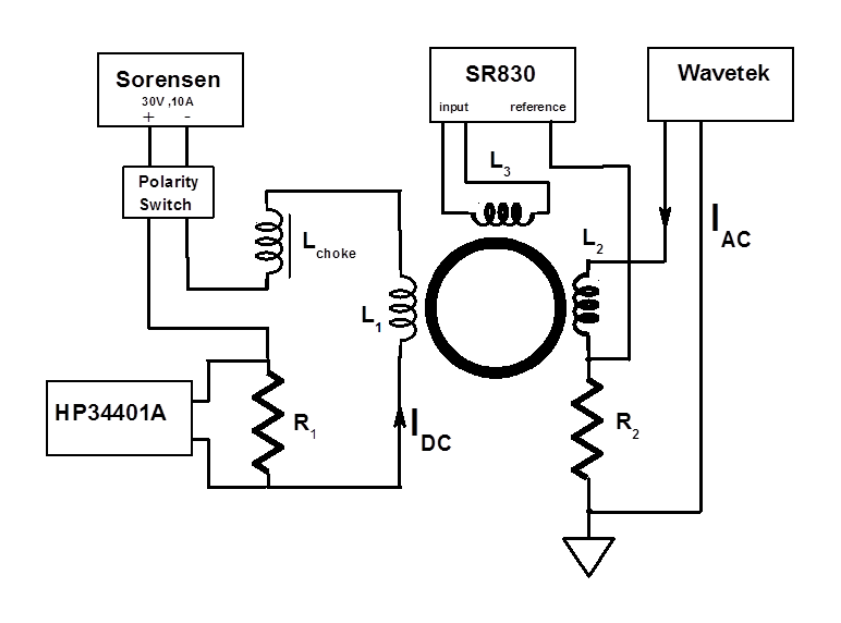
Current in primary coil in A

From permeability to B-H hysteresis loop

Step#3. What we are measuring? Calibration.

Lock-in measures emf on the pickup coil

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

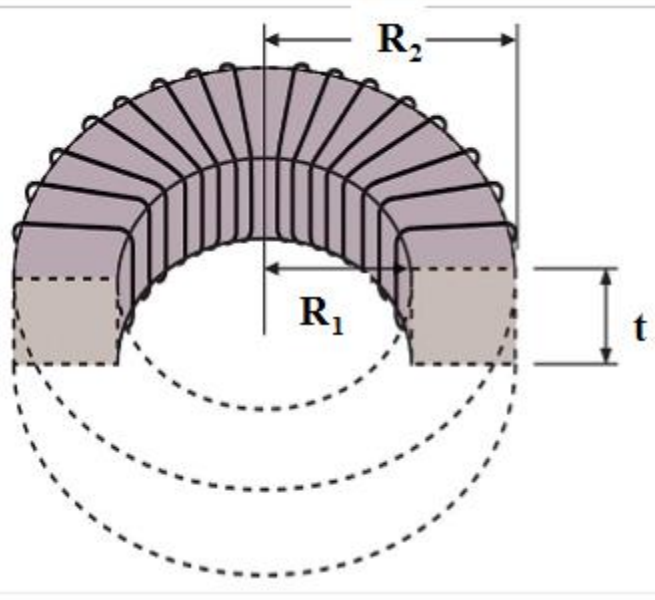


Here Ip is ac current in primary coil L3; $I_p = \frac{V_0 \sin(\omega t)}{R_2}$

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 dΦ



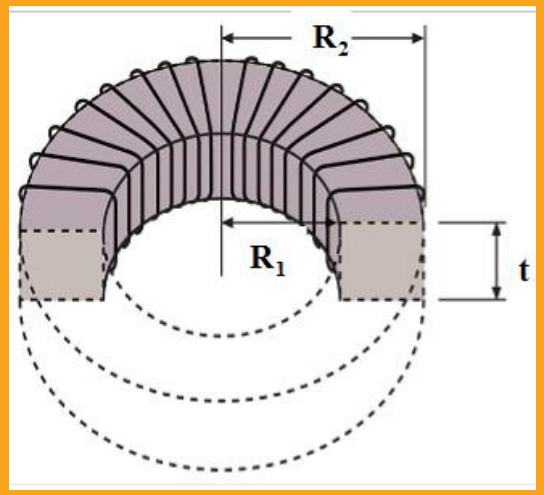
For toroid: $$H = \frac{N_p I_p}{2\pi r}$$

$R_2 < r < R_1$

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

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

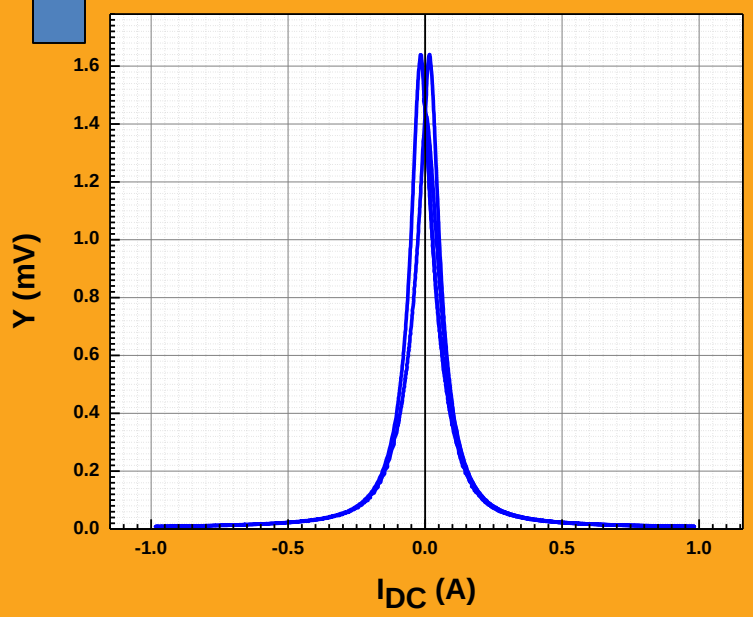
Inductance of the toroid:

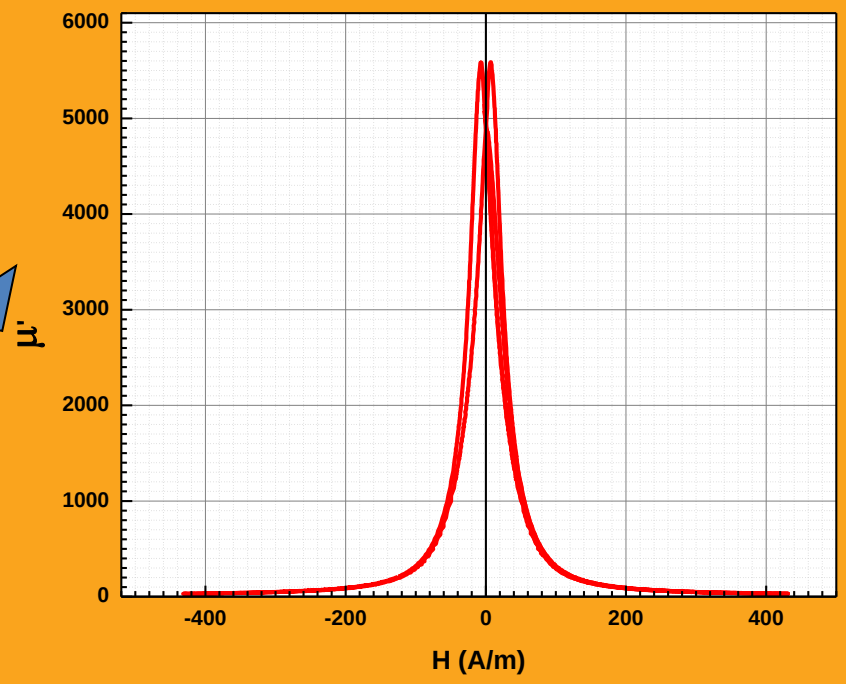
$$L = \frac{\Phi}{I}; \quad L = \mu_r L_0 = (\mu' - i\mu'') L_0$$

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

From permeability to B-H hysteresis loop

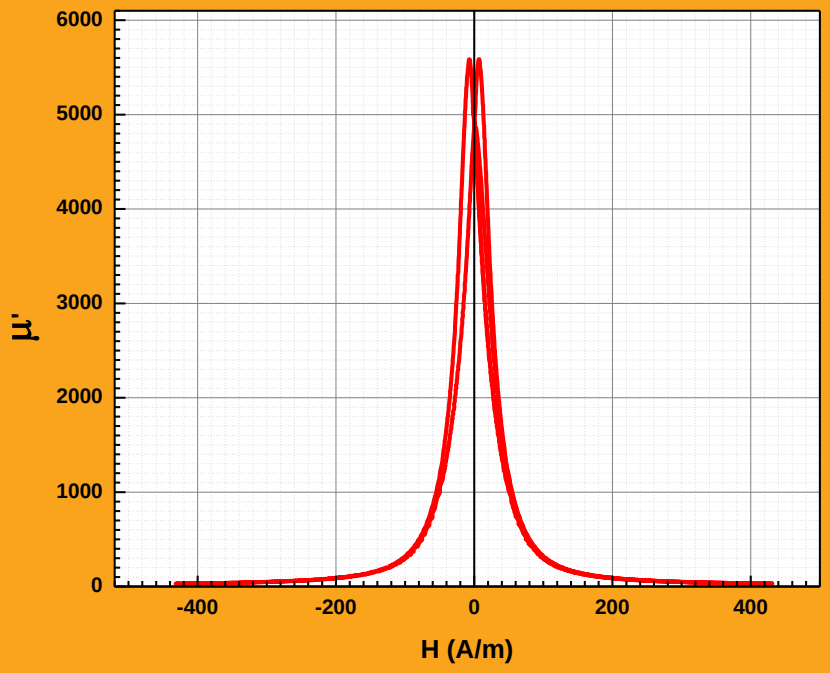
$$V_{lock-in} = \mu_r L_0 \frac{dI_p}{dt}$$





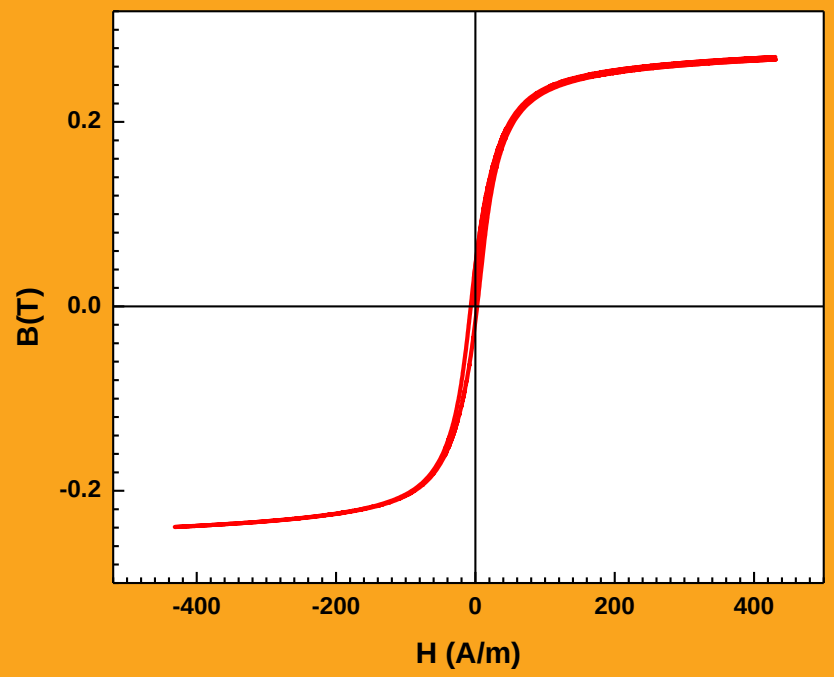
$$H_0 = \frac{N_p I_{DC}}{2\pi r}$$

From permeability to B-H hysteresis loop



Step#4. From μ_r(H) to B-H

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

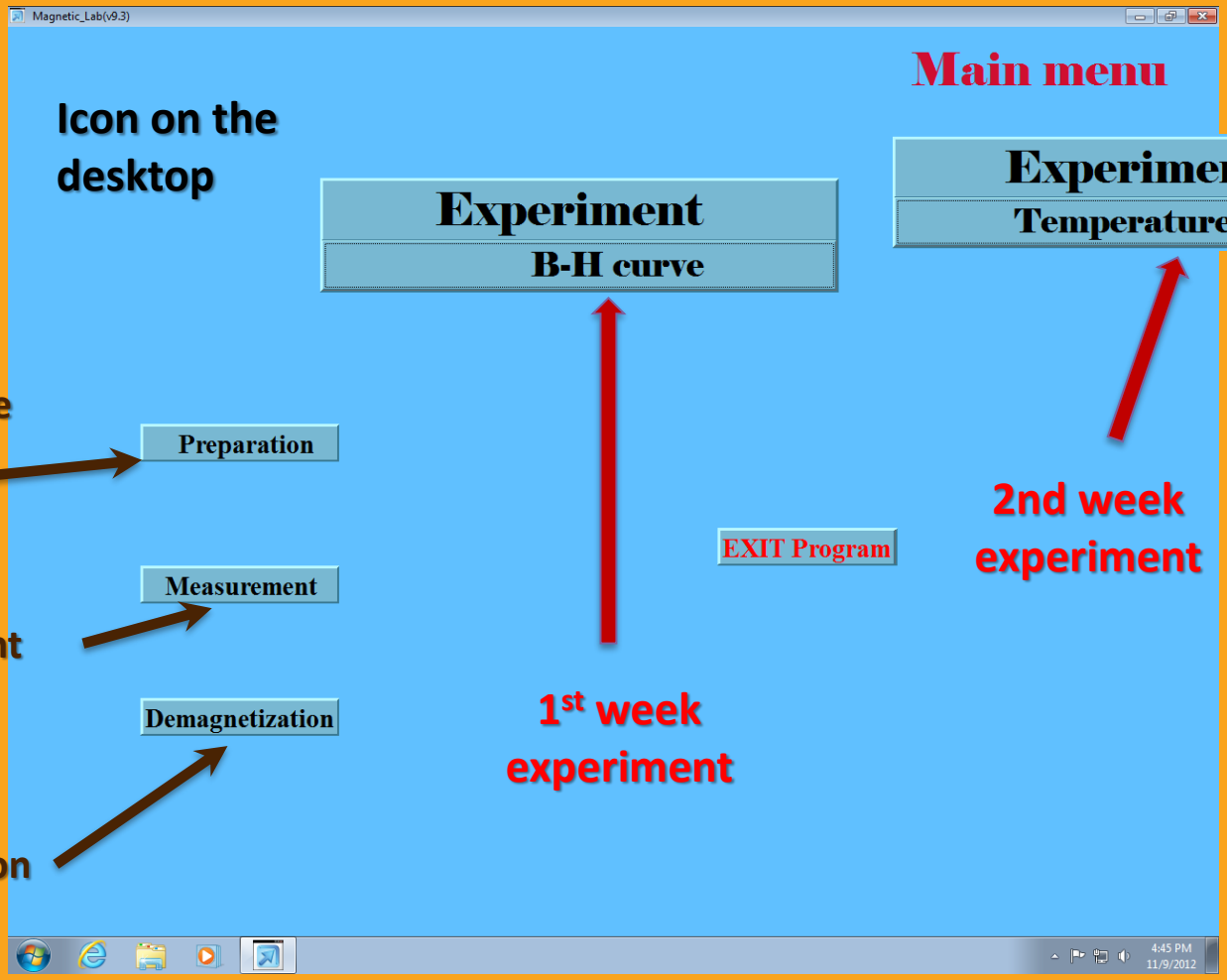


After integrating →

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

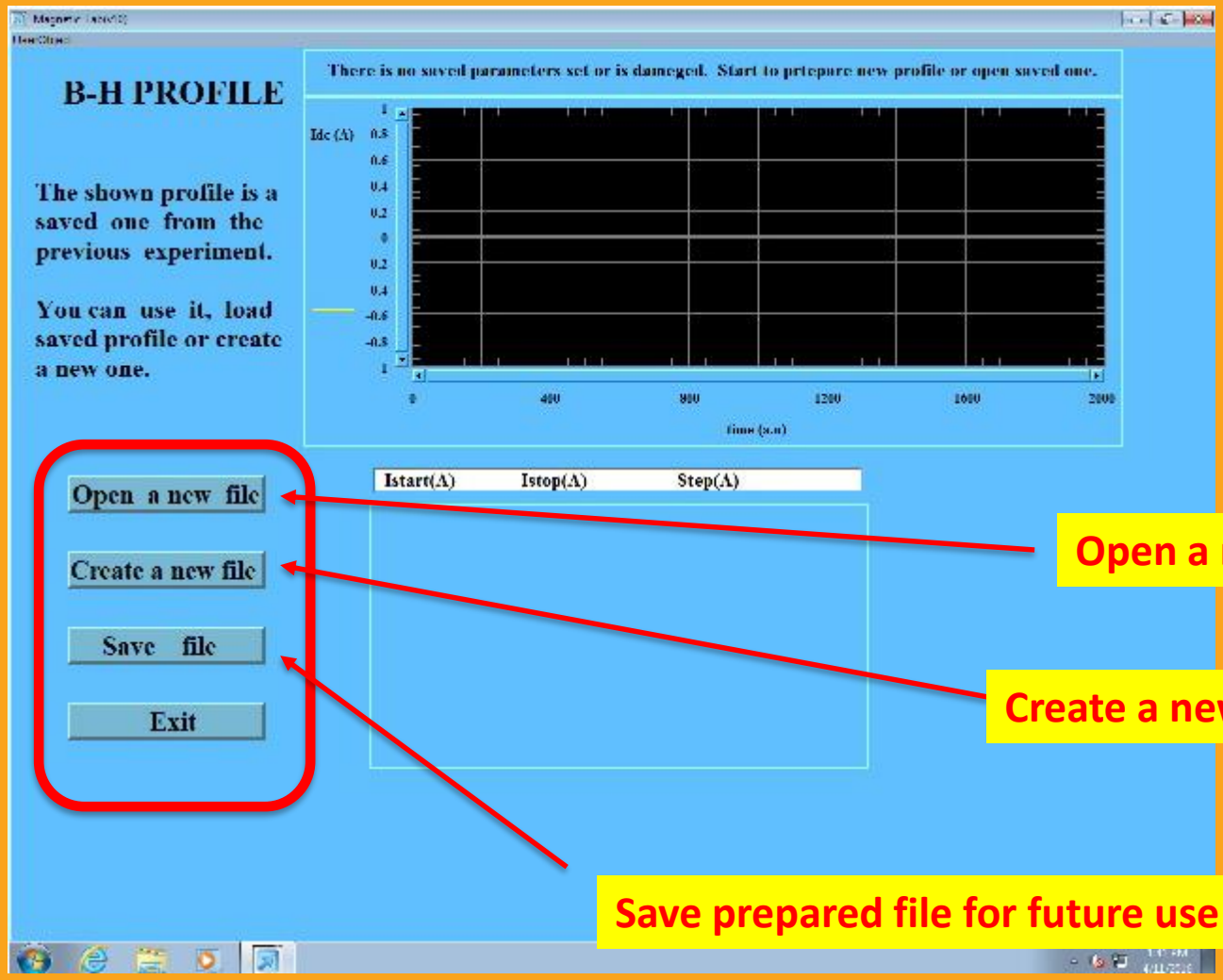
Software issue

Magnetic Lab v9.2



Software issue

Measuring profile preparation. Using profile template



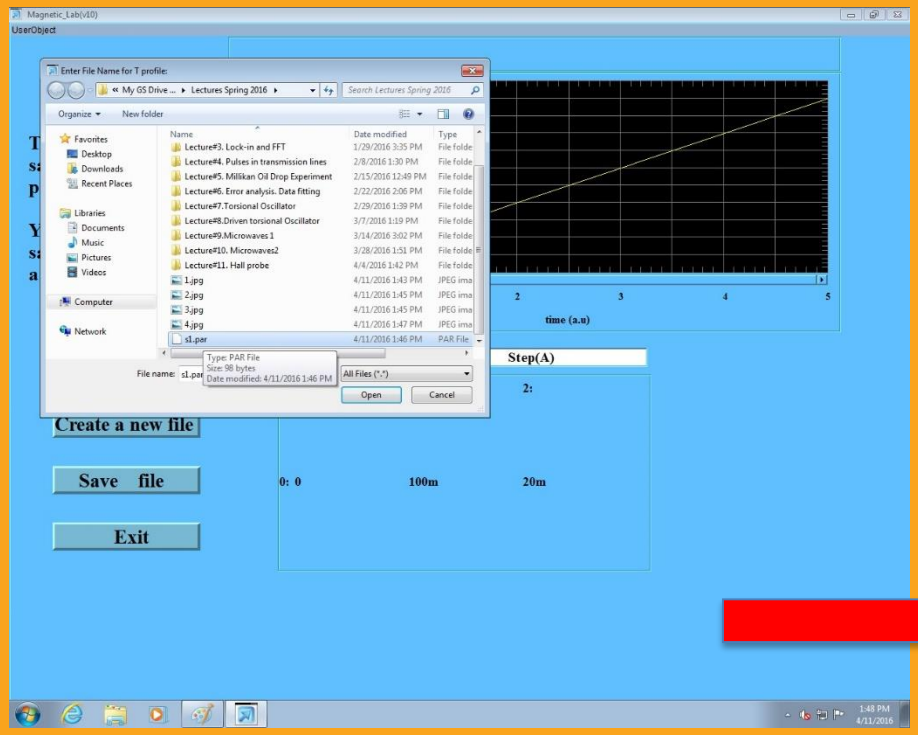
Open a new file

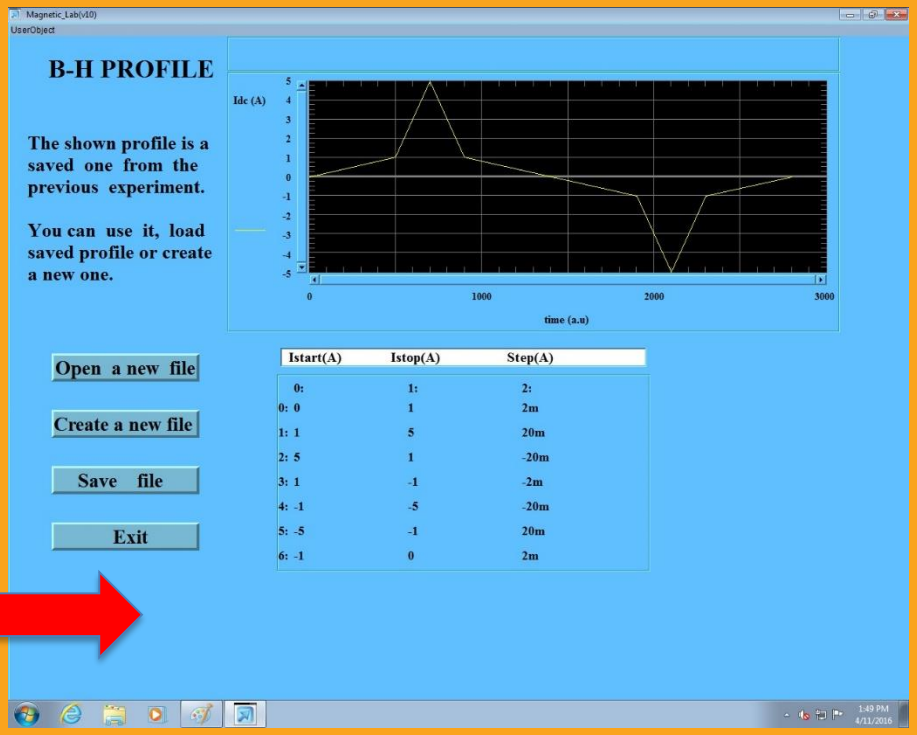
Create a new file

Save prepared file for future use

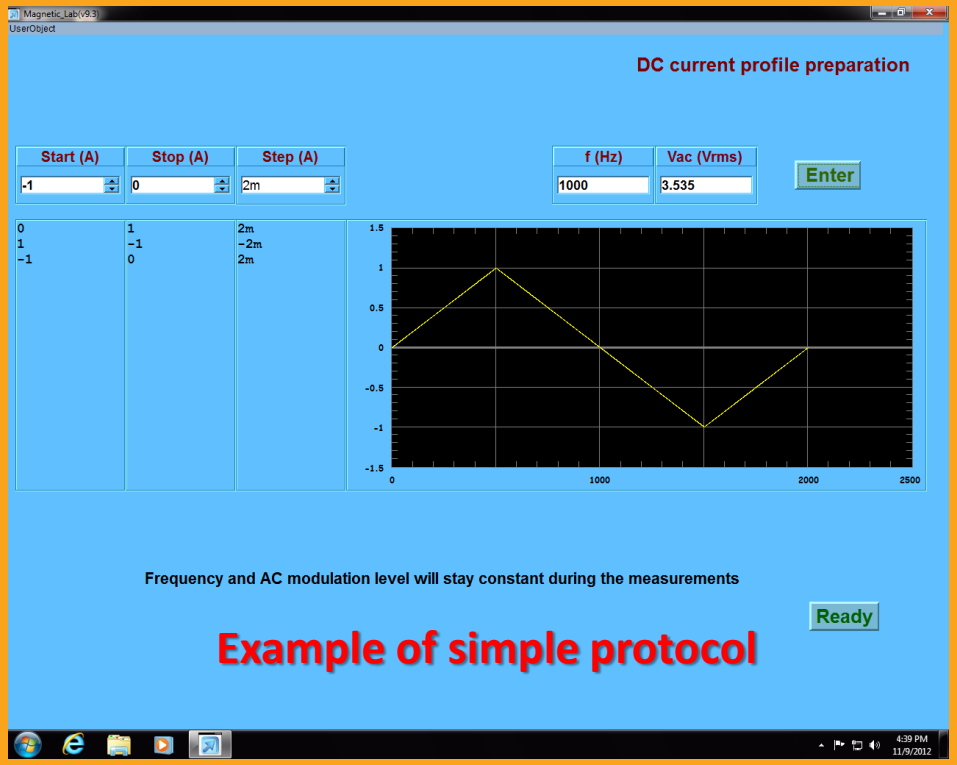
Software issue

Measuring profile preparation. Using profile template.

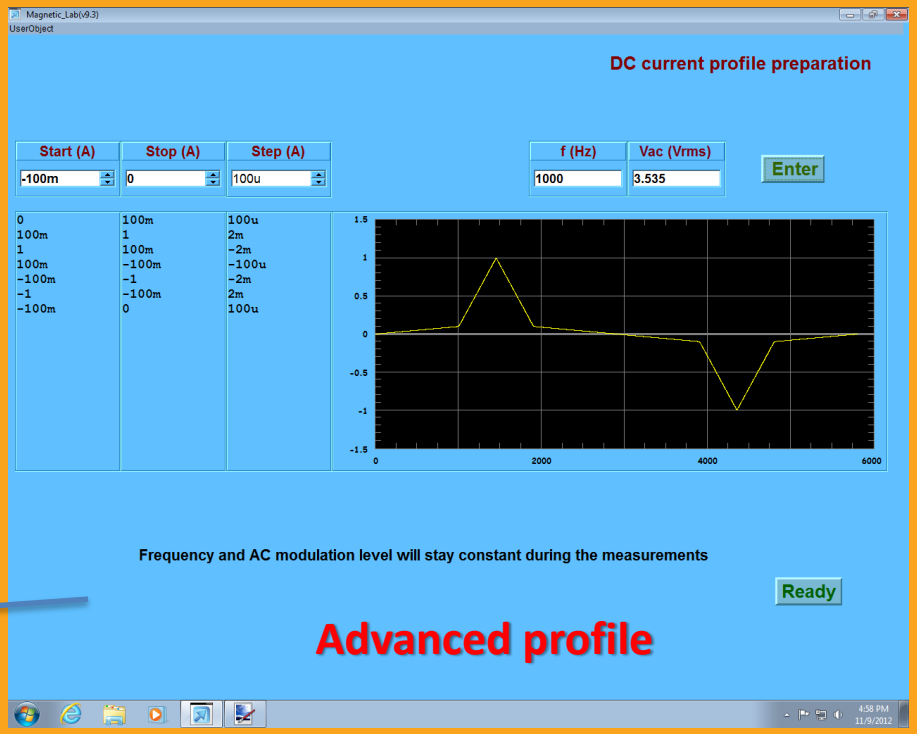


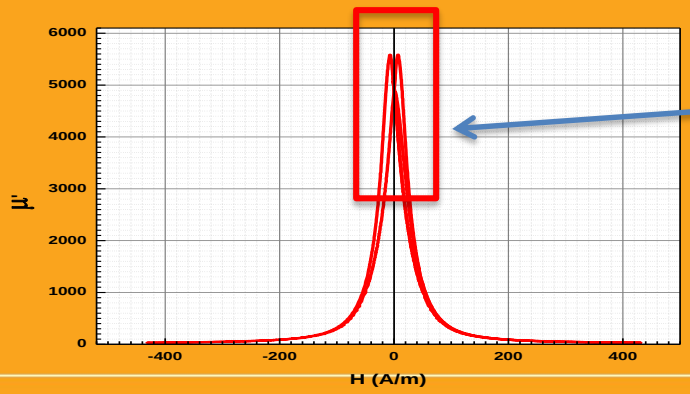


Software issue

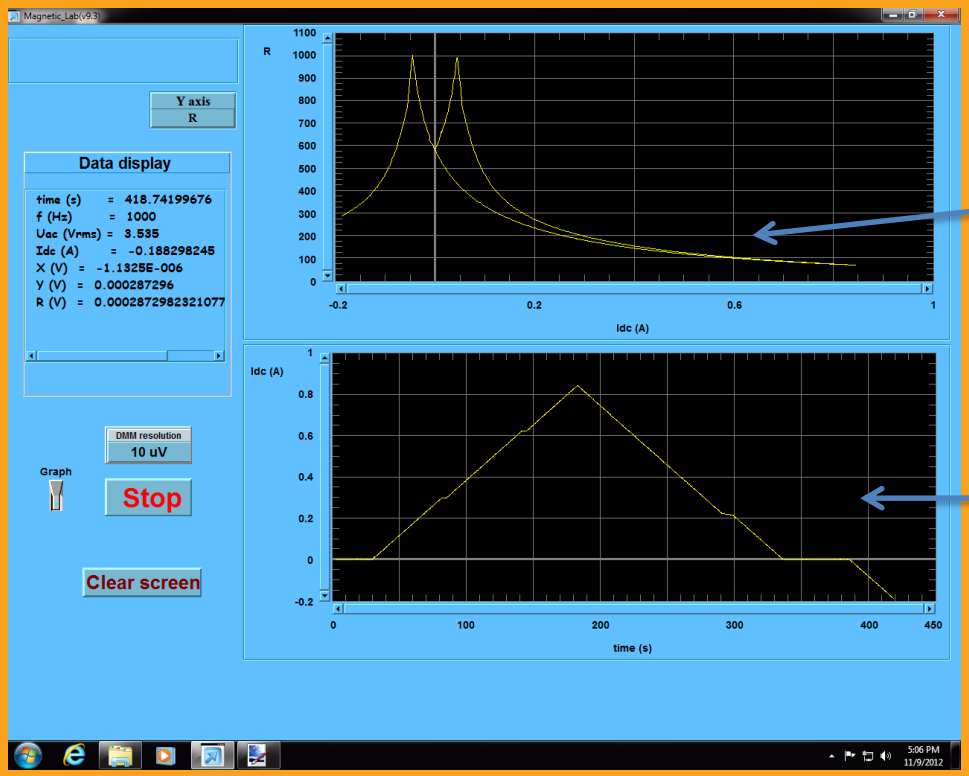


Measuring profile preparation





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	-1.22035E-	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.otw

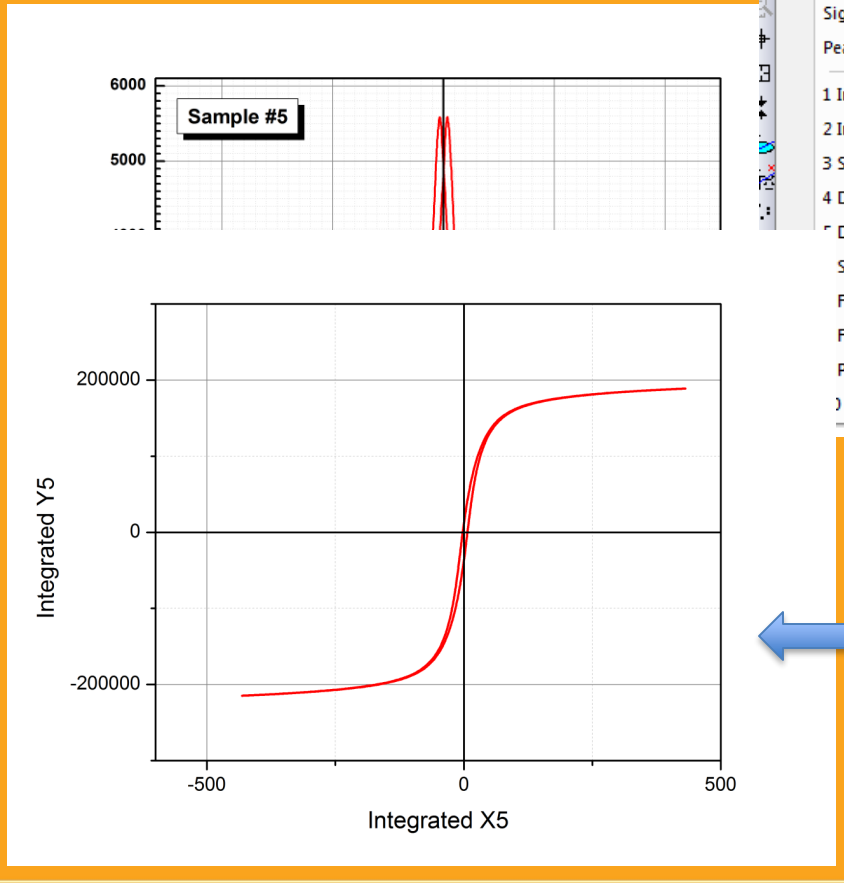
It does not contain the equations – you have to write them

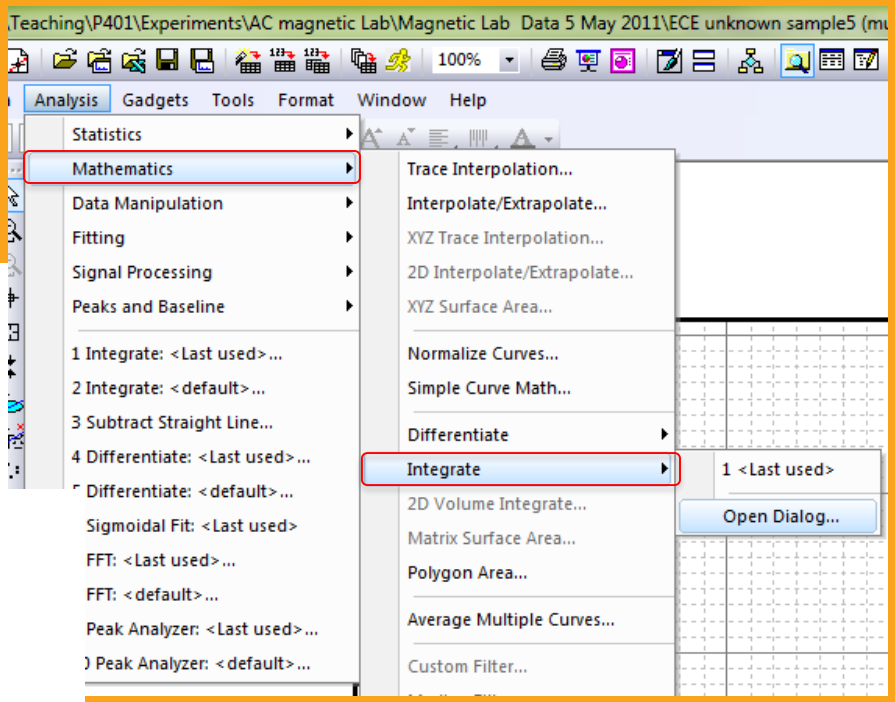
	times(X)	fHz(Y)	UacVrms(Y)	IdcA(Y)	XV(Y)	YV(Y)	RV(Y)	A(L)	B(Y)	Lo(Y)	mu1(Y)	mu2(Y)	H(Y)
ng N	time (s)	f (Hz)	Uac (Vrms)	Idc (A)	X (V)	Y (V)	R (V)						a/m
Units								Parameters					
1	2.125	1000	3.535	0.00444	-1.31876E-6	7.73077E-5	7.73189E-5	Npickup	20	3.35179E-7	51.92141	0.88571	0.00789
2	12.828	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

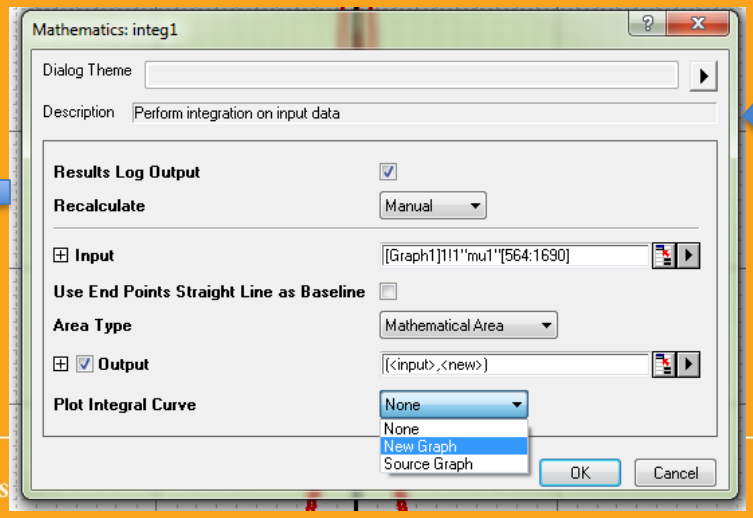
Raw data **Parameters** **Calculated results**

Data analysis using Origin. Integrating.

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

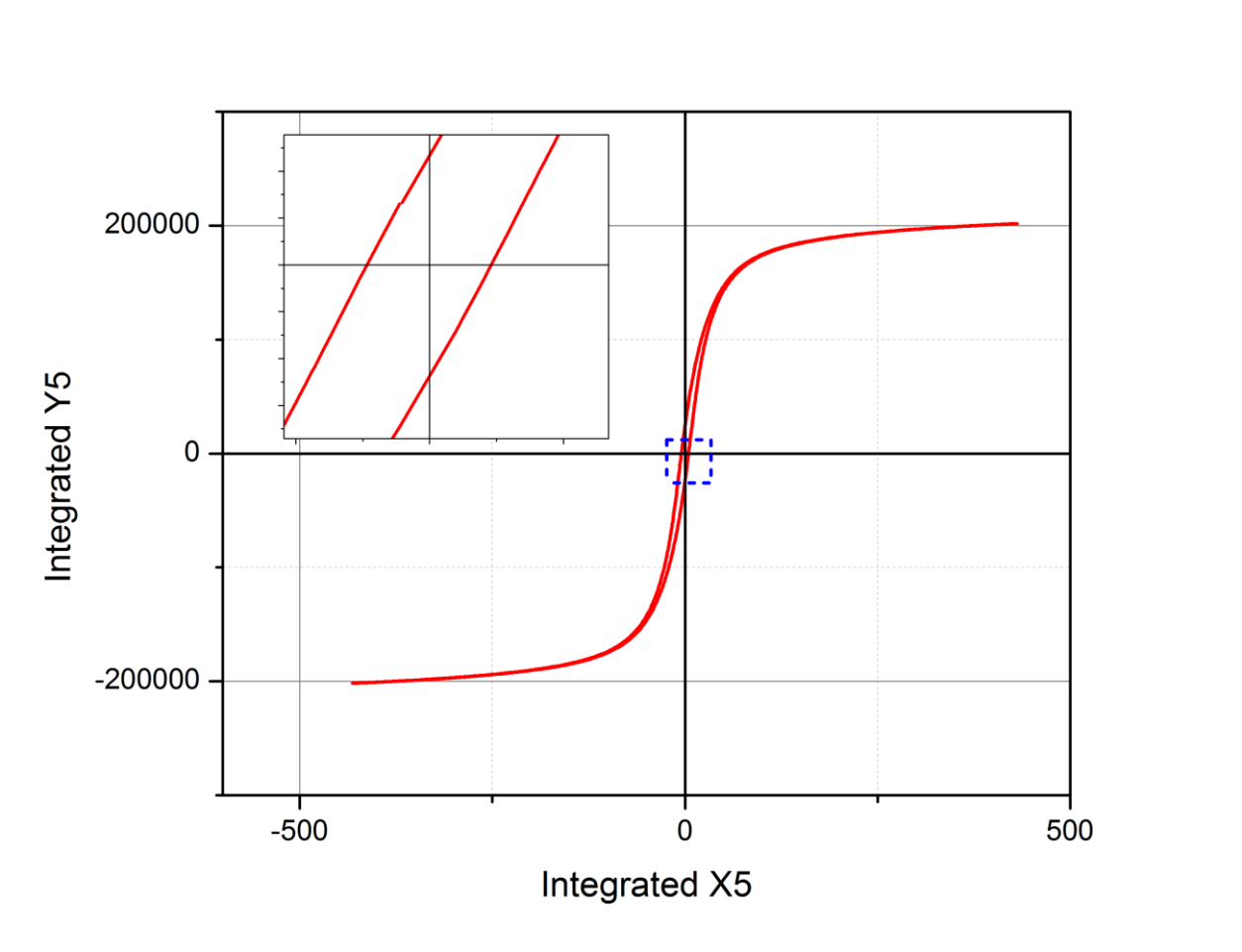






Data analysis using Origin. Integrating.

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



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**