



UNIVERSITY OF ILLINOIS  
AT URBANA-CHAMPAIGN

ALMA MATER

TO THY HAPPY CHILDREN  
OF THE FUTURE  
THOSE OF THE PAST  
SEND GREETINGS

# AC Measurement of Magnetic Susceptibility

**Physics 401, Spring 2019**  
**Eugene V. Colla**

[illinois.edu](http://illinois.edu)



# Outline

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



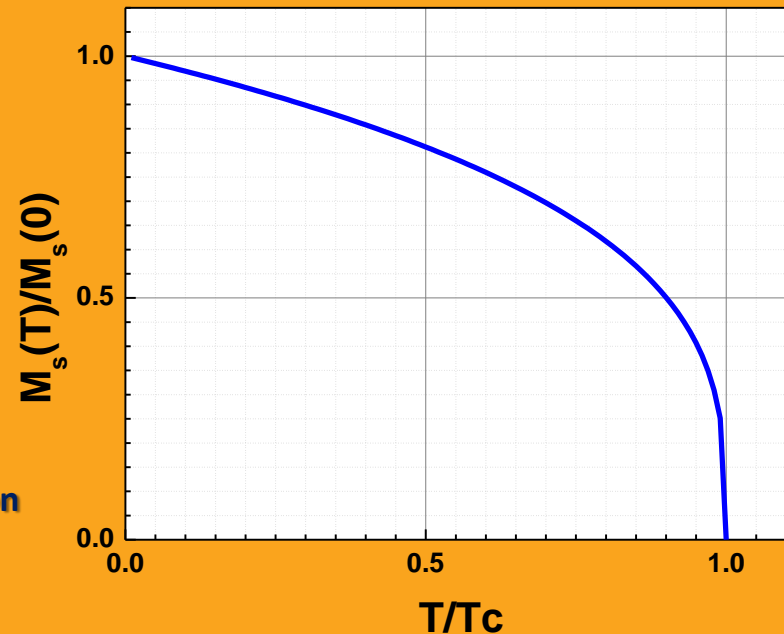
# Ferromagnetism. Definition.

Some materials below a **certain temperature ( $T_c$ )** 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**

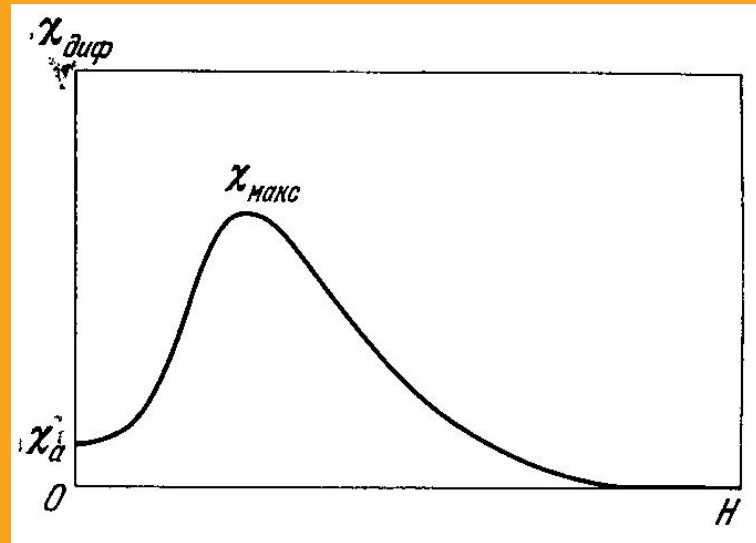
Typical behavior of spontaneous magnetization as function of temperature



# Ferromagnetic materials.



Aleksandr Stoletov  
(1839 –1896)



“Stoletov” curve

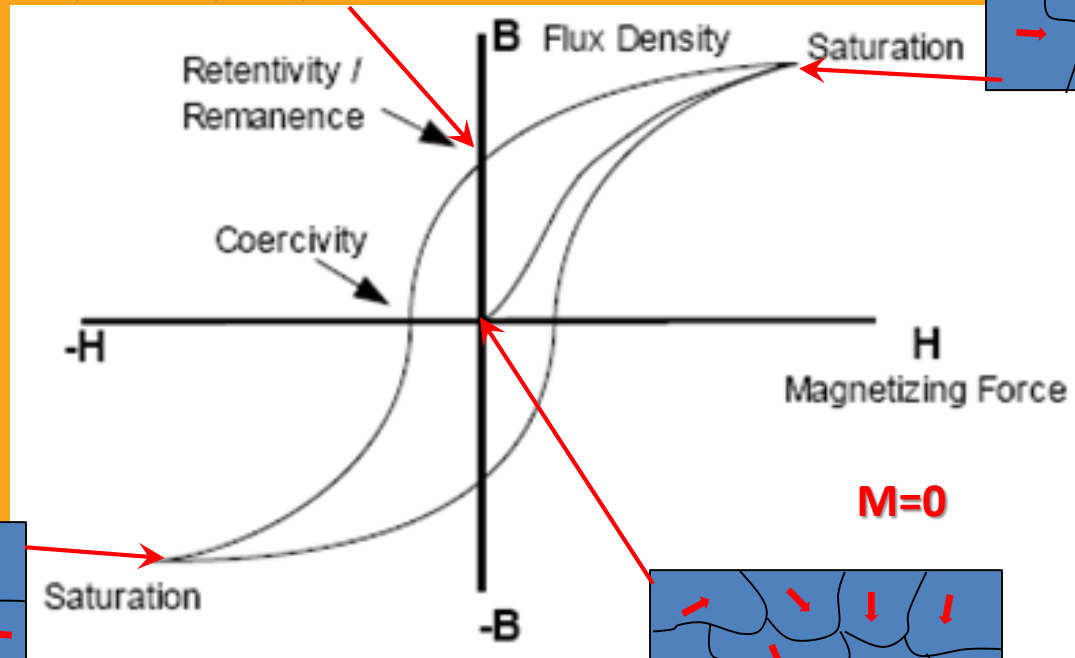
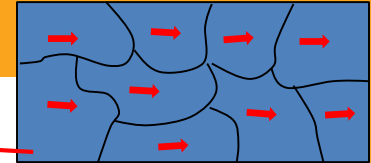
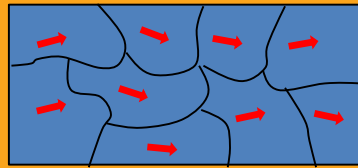
$$\chi = \frac{dM}{dH}$$

Material	Curie temp. (K)
Co	1388
Fe	1043
Fe <sub>2</sub> O <sub>3</sub> *	948
FeOFe <sub>2</sub> O <sub>3</sub> *	858
NiOFe <sub>2</sub> O <sub>3</sub> *	858
MgOFe <sub>2</sub> O <sub>3</sub> *	713
MnBi	630
Ni	627
MnSb	587
MnOFe <sub>2</sub> O <sub>3</sub> *	573
Y <sub>3</sub> Fe <sub>5</sub> O <sub>12</sub> *	560
CrO <sub>2</sub>	386
MnAs	318
Gd	292

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

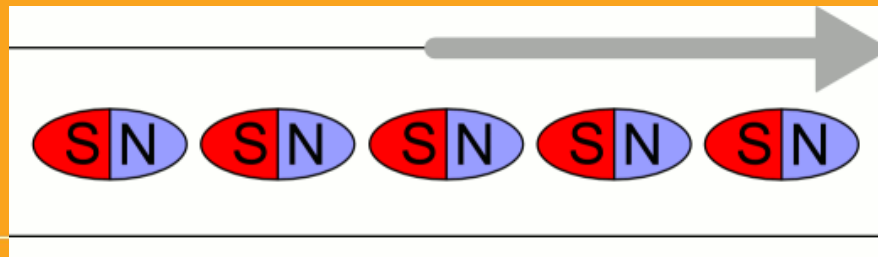
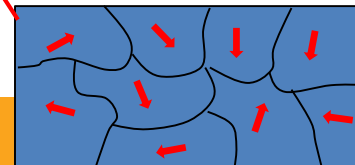
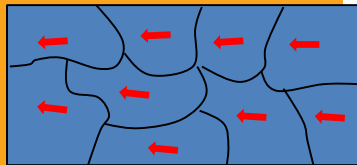
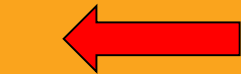


# Domains. Hysteresis loop.



$$M \sim M_s$$

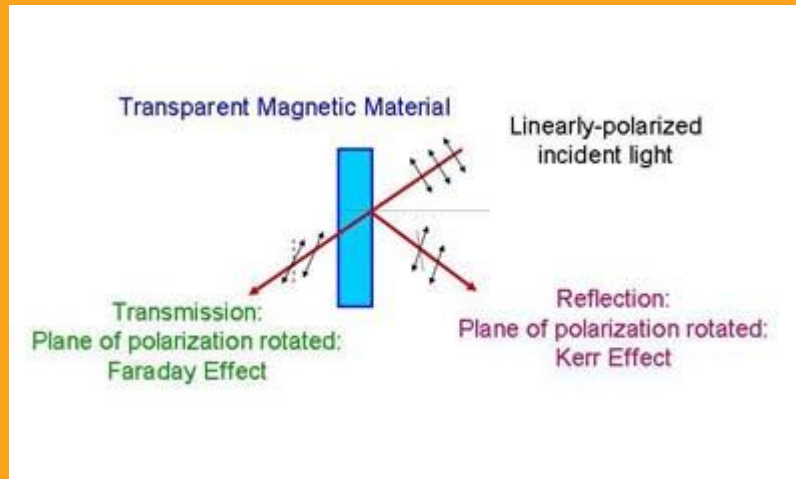
$$M=0$$



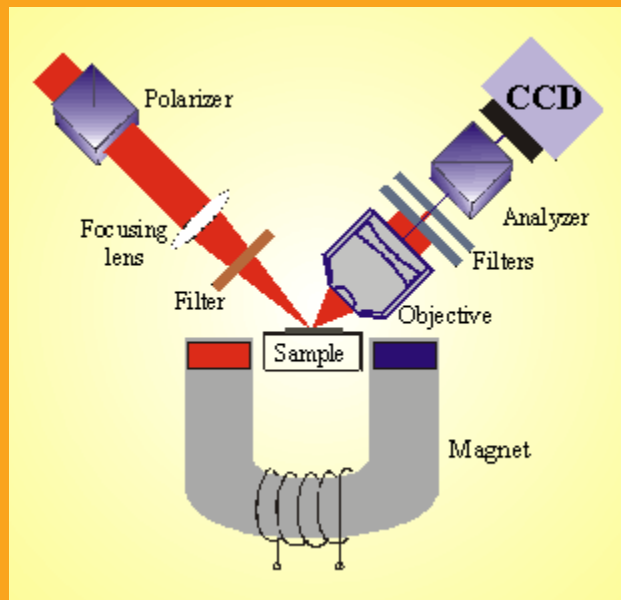
\* Courtesy Wikipedia



# Kerr Effect. Visualization of the Domains



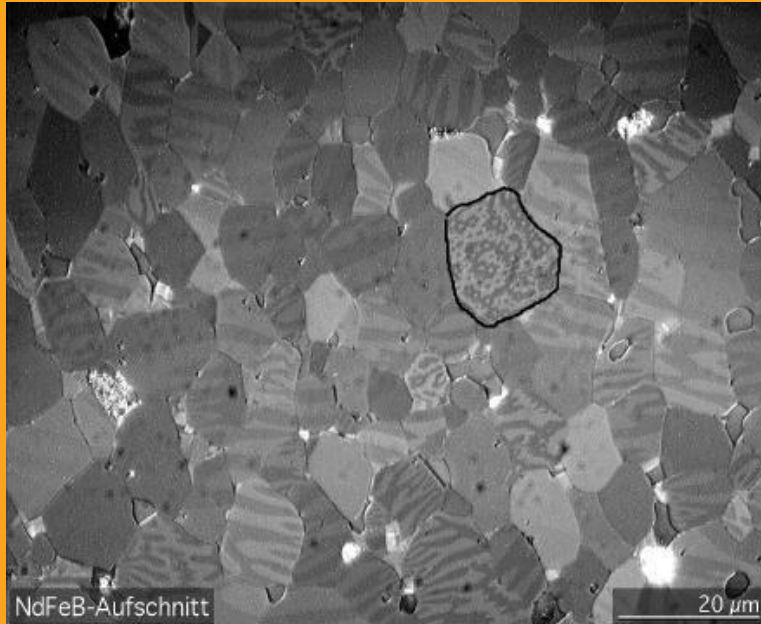
**John Kerr**  
**17 Dec 1824 –**  
**15 Aug 1907**



The Diagram of Typical Kerr Microscope

Courtesy of Radboud University, Nijmegen  
The Netherlands

# Domains



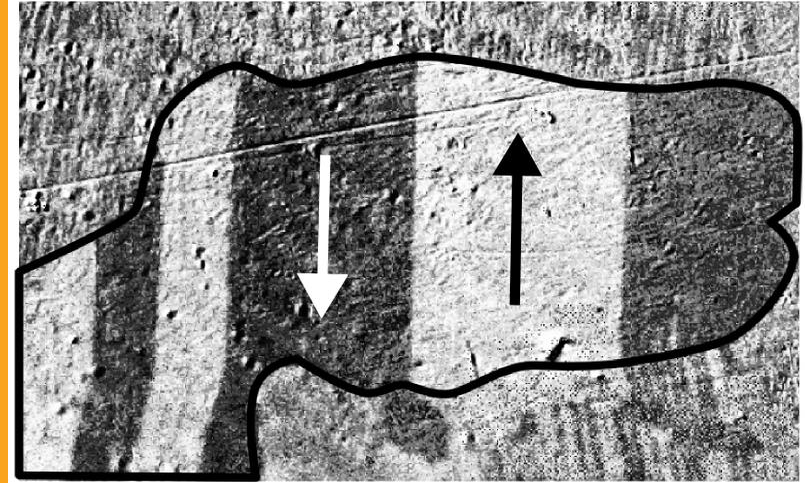
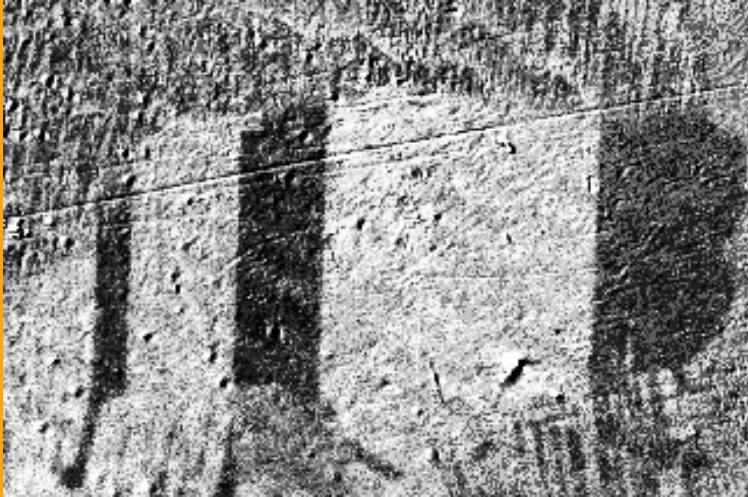
Several grains of NdFeB with magnetic domains made visible via contrast with a Kerr microscope.

Courtesy of Wikipedia



Kerr microscope  
Courtesy of University of  
Uppsala (Sweden)

# Domains



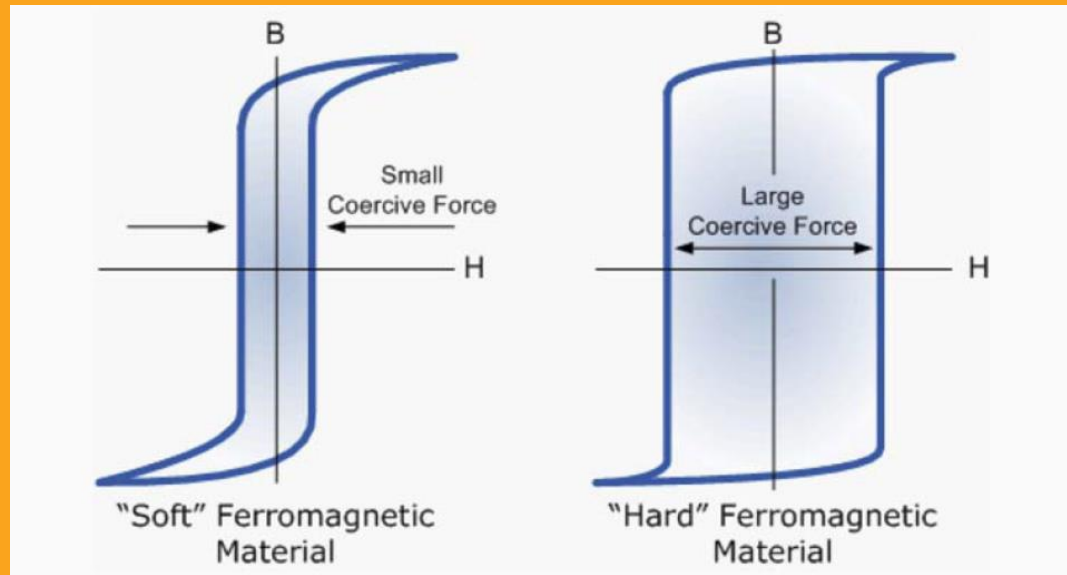
**Moving domain walls in a grain of silicon steel caused by an increasing external magnetic field**

Courtesy of Wikipedia



# Hysteresis Loops.

## Remagnetization loses



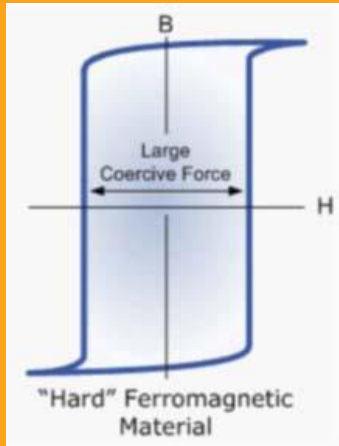
Energy of the magnetic field

$$W = V \int H dB$$

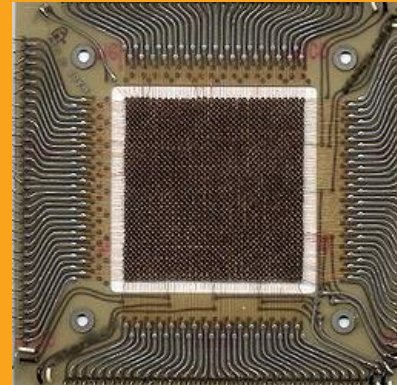
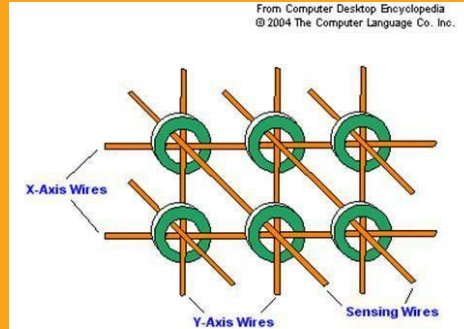
By cycling around the loop

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

# “Hard” materials. Application.



### RAM memory



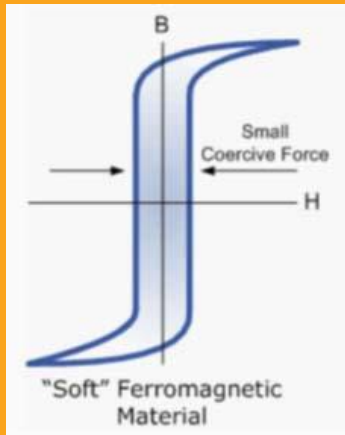
### Permanent magnets



### 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  $M(H)$

$$M = \chi H$$

$\chi$  – magnetic susceptibility,  
in general  $\chi(H)$

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

$$\mu_r = 1 + \chi$$

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

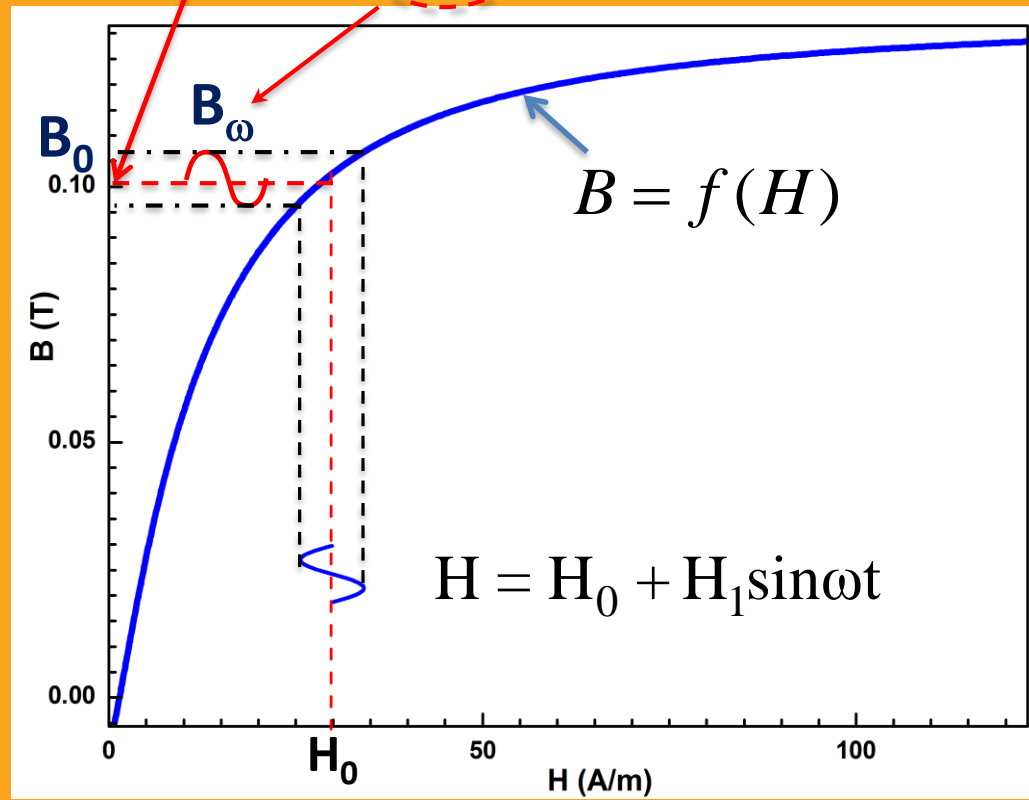


# Modulation Spectroscopy

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

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

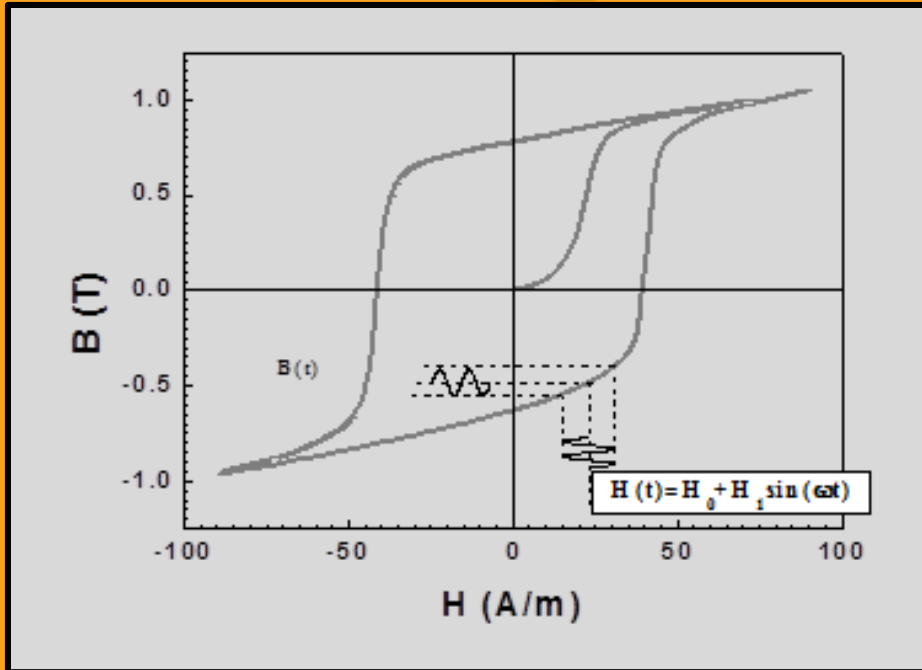
$$H_1 = \text{const}$$



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



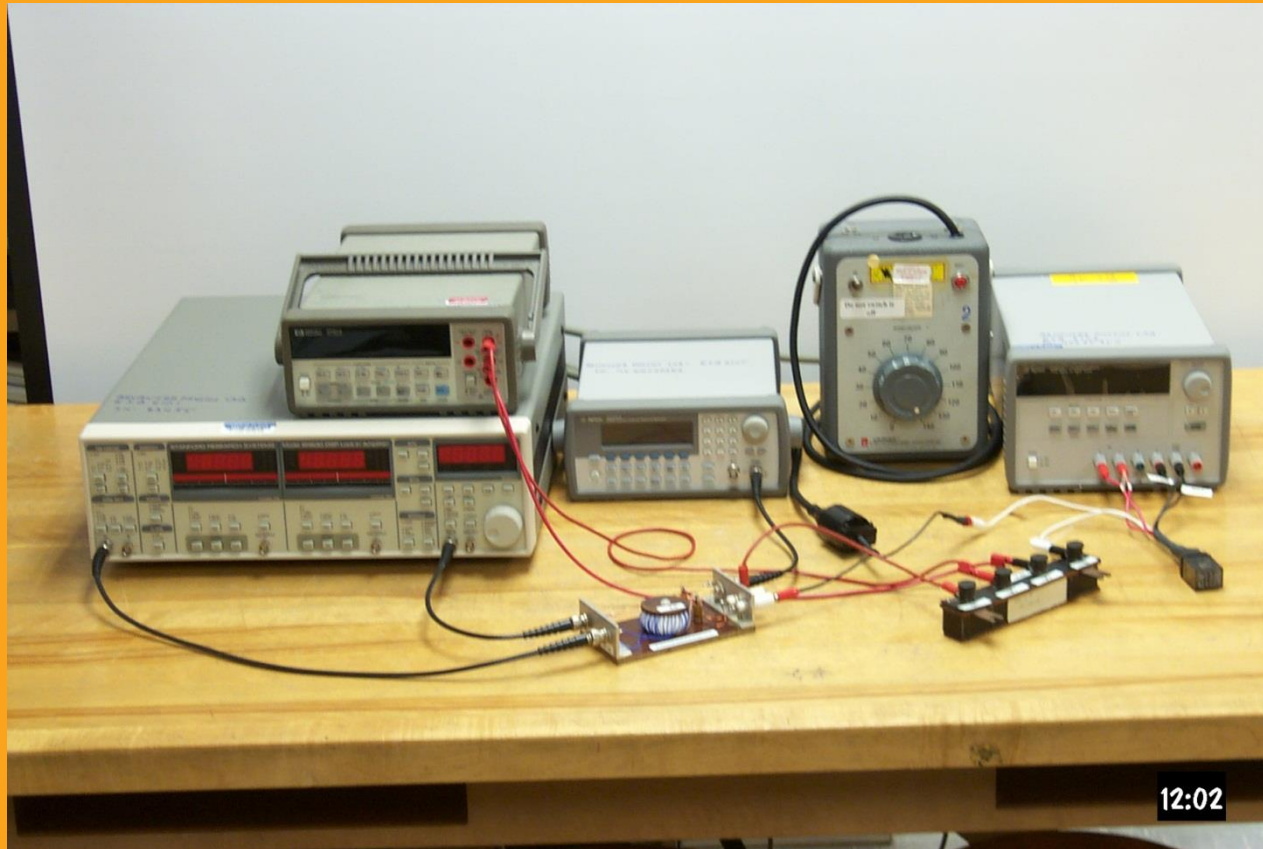
# Measuring the magnetic permeability



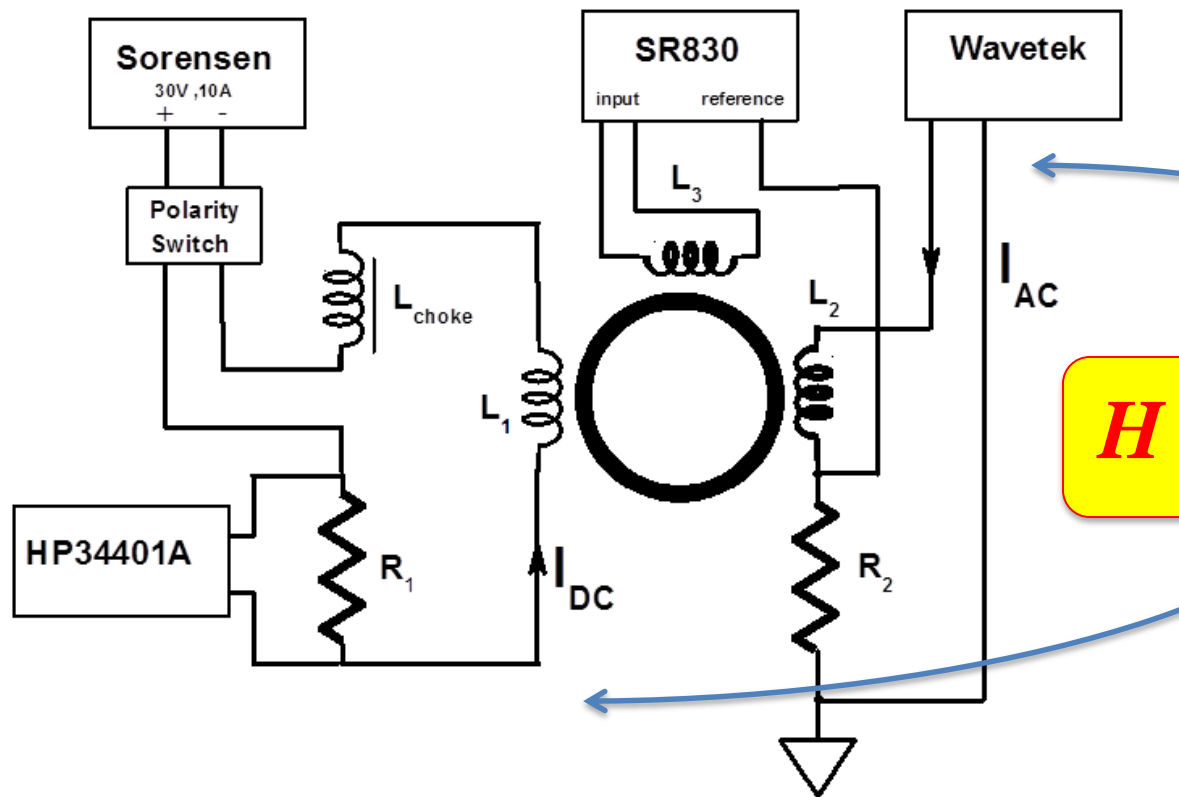
By applying a small modulation of the  $H$  field we can measure the derivative of the  $B$ - $H$  hysteresis loop or dependence of the magnetic permeability on  $H$  field

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

# Setup #1. Investigation of the hysteresis loops.



# Setup #1. Investigation of the hysteresis loops.

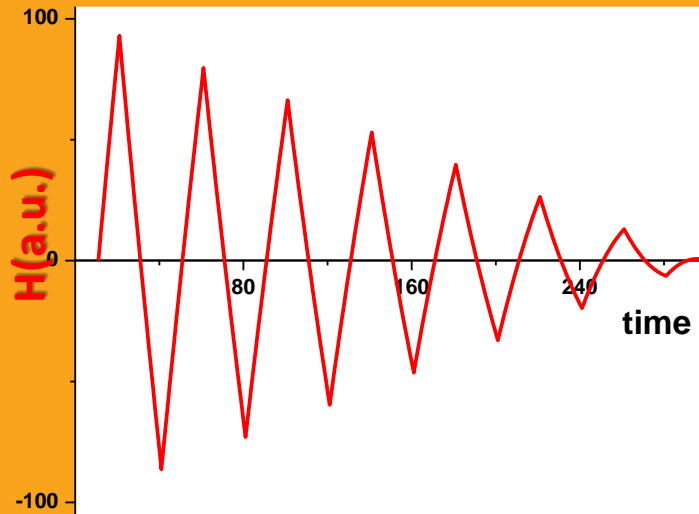


$$H = \frac{N_p I_p}{2\pi r}$$

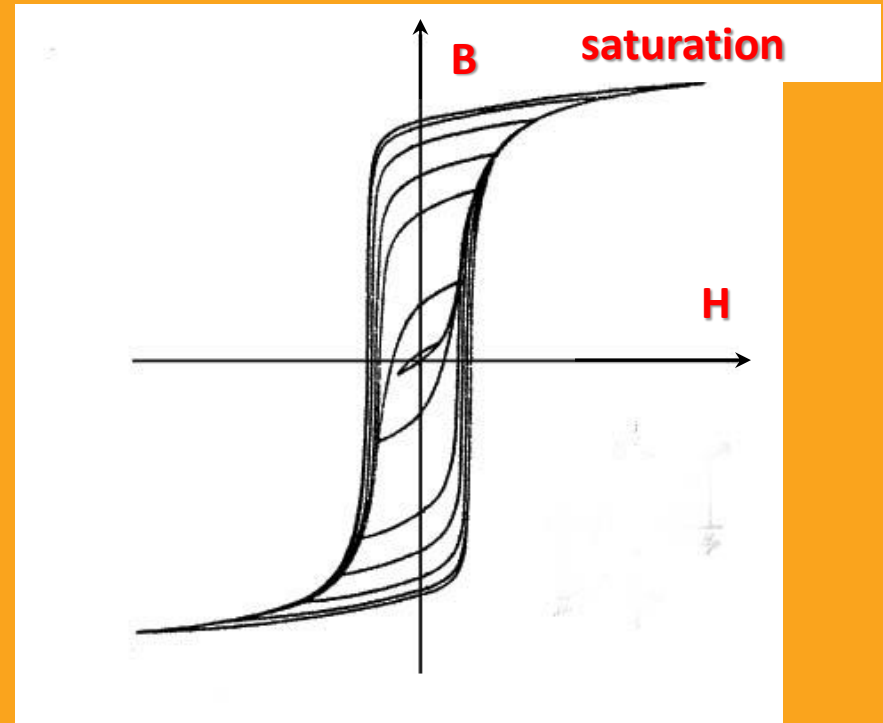
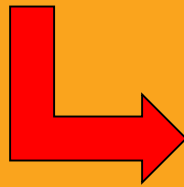
$$H = H_0 + H_1 \cos \omega t$$



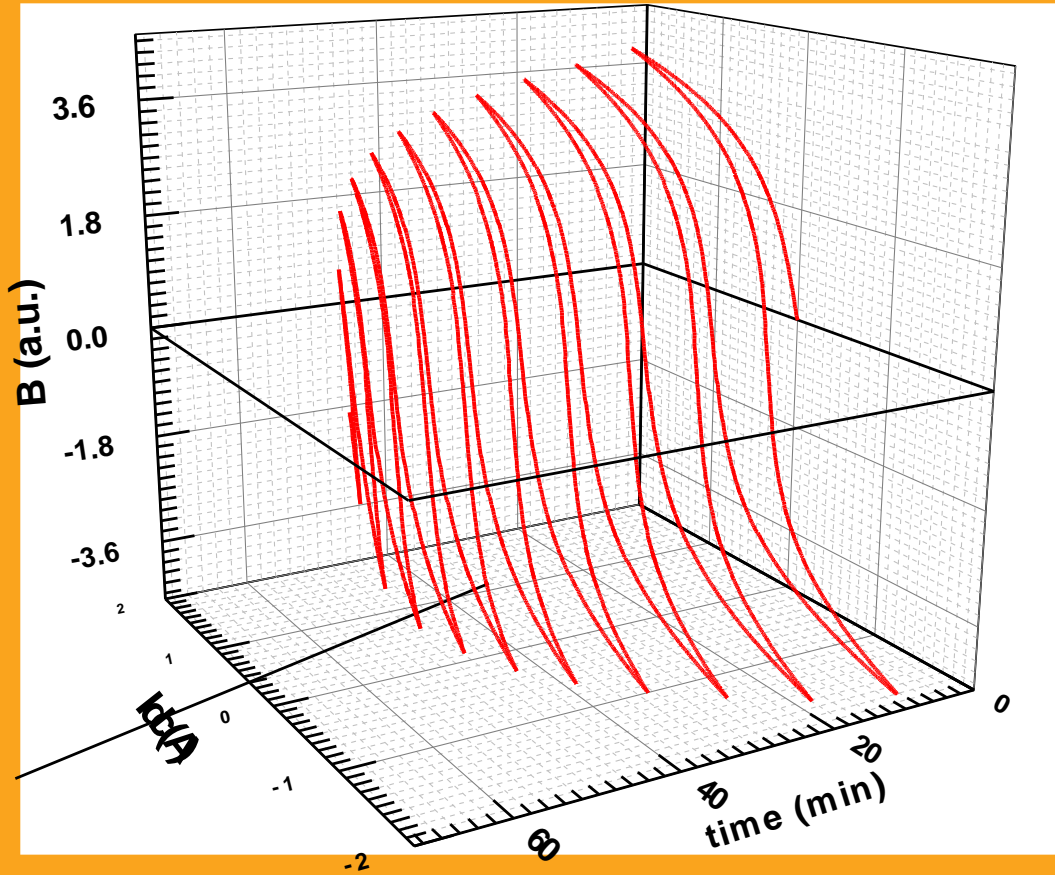
# Major/minor loops. Demagnetization



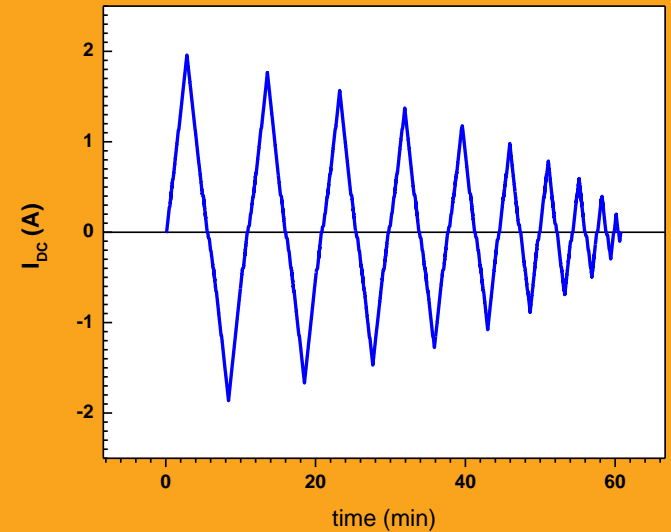
Waveform of H-field



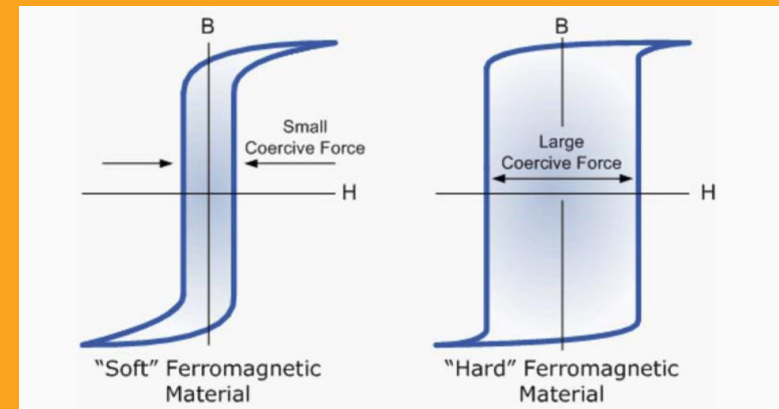
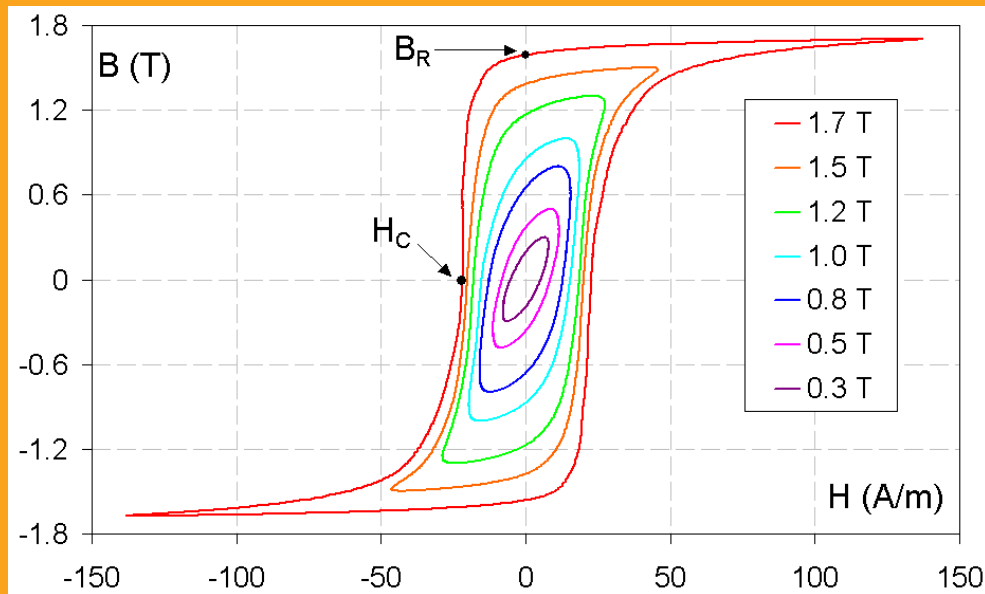
# Demagnetization



Demagnetization of 4C65 toroid  
from Ferroxcube

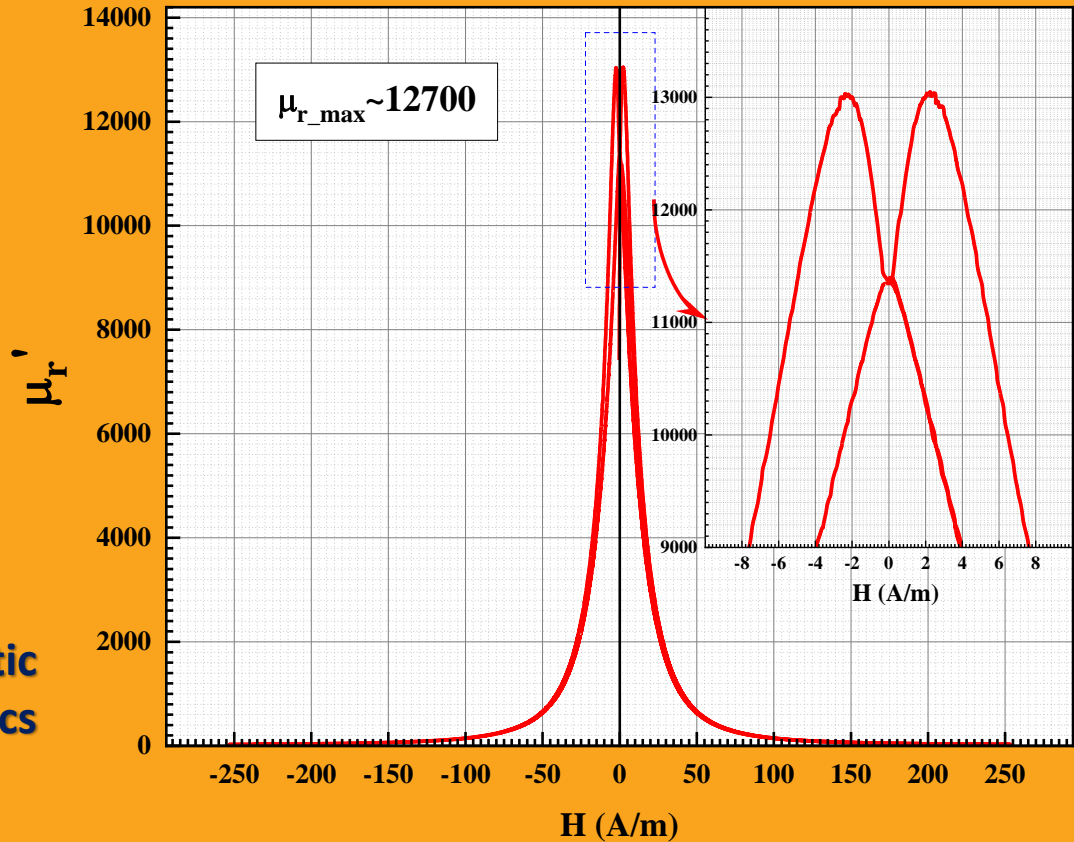
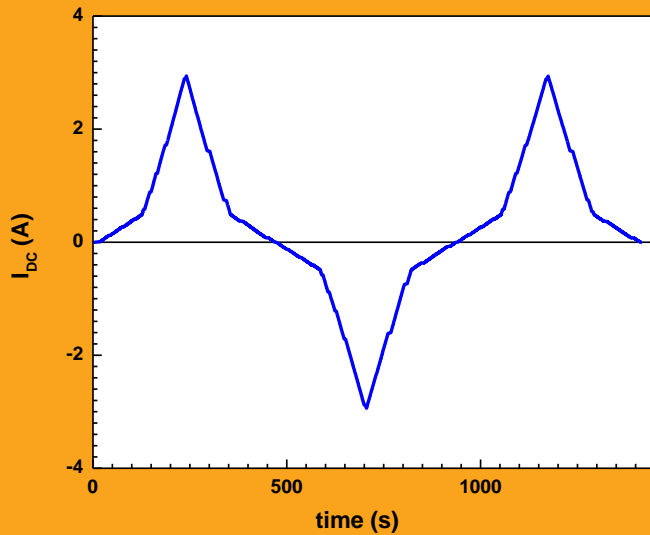


# Hysteresis Loops



**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

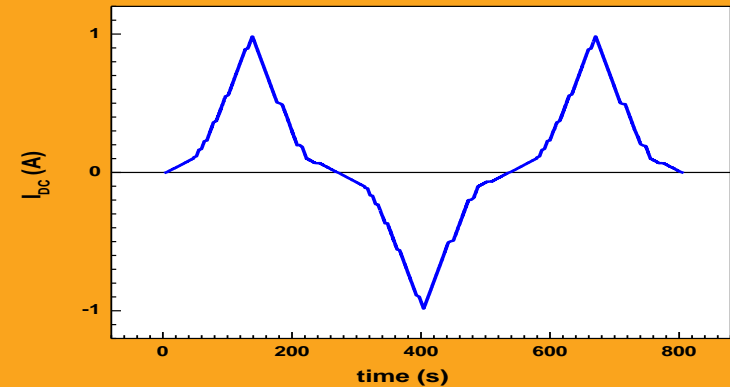


DC current profile and magnetic permeability of Magnetics ZW44715TC

# From permeability to B-H hysteresis loop

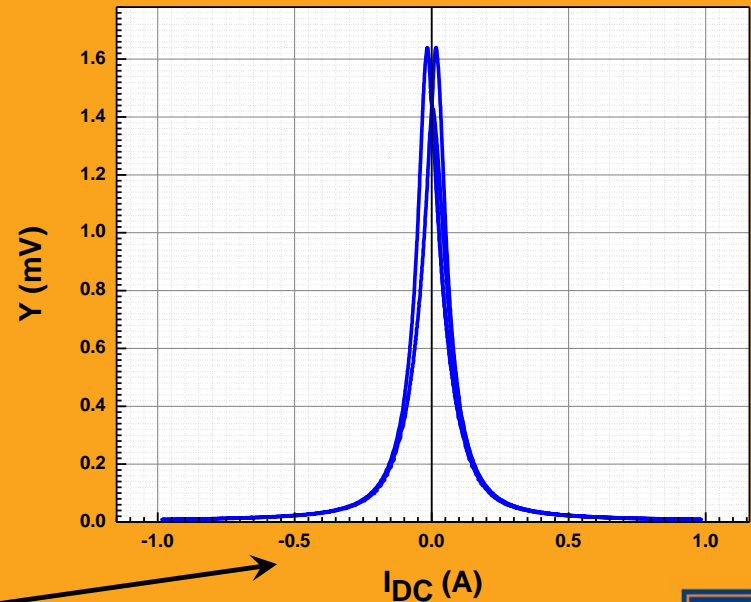
**Step#1. Performing one fast IDC scan the based on the result preparing the “smart” IDC profile**

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

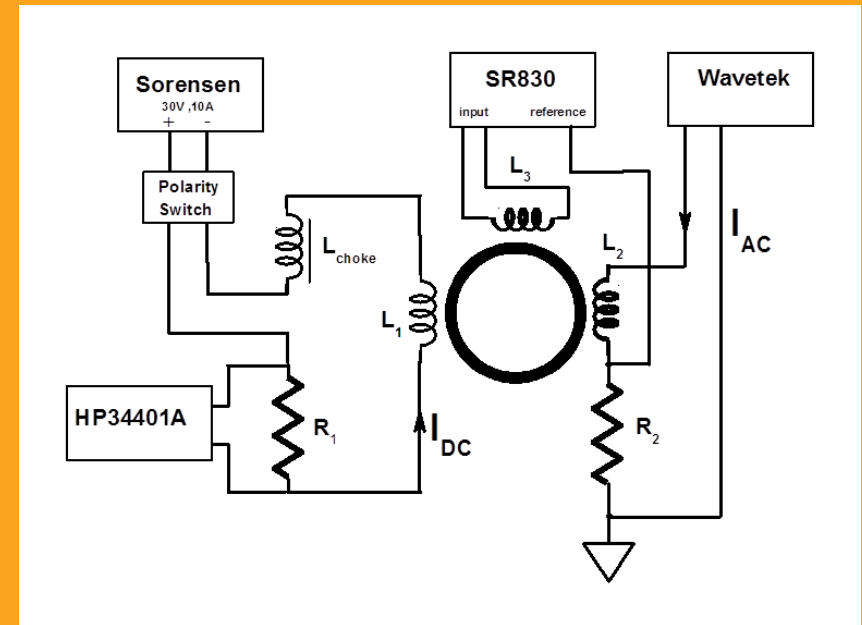


# From permeability to B-H hysteresis loop

Step#3. What we are measuring?  
Calibration.

Lock-in measures emf on the pickup coil

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



Here  $I_p$  is ac current in primary coil L<sub>3</sub>;  $I_p = \frac{V_0 \sin(\omega t)}{R_2}$

# From permeability to B-H hysteresis loop

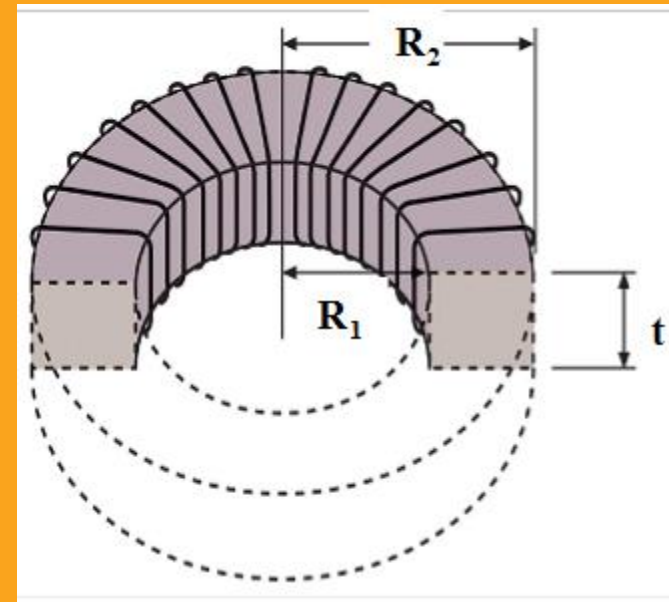
Step#3. What we are measuring?  
Calibration.

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

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

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

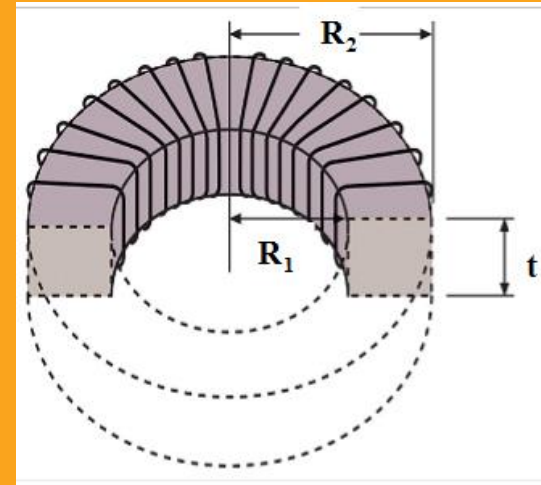
$$da = dr * t$$



$$R_2 < r < R_1$$

# From permeability to B-H hysteresis loop

Step#3. What we are measuring?  
Calibration.



Total flux detected by pickup coil:

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

$N_p$  and  $I_p$  number of turns of AC primary coil and AC rms current

Inductance of the toroid:

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

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

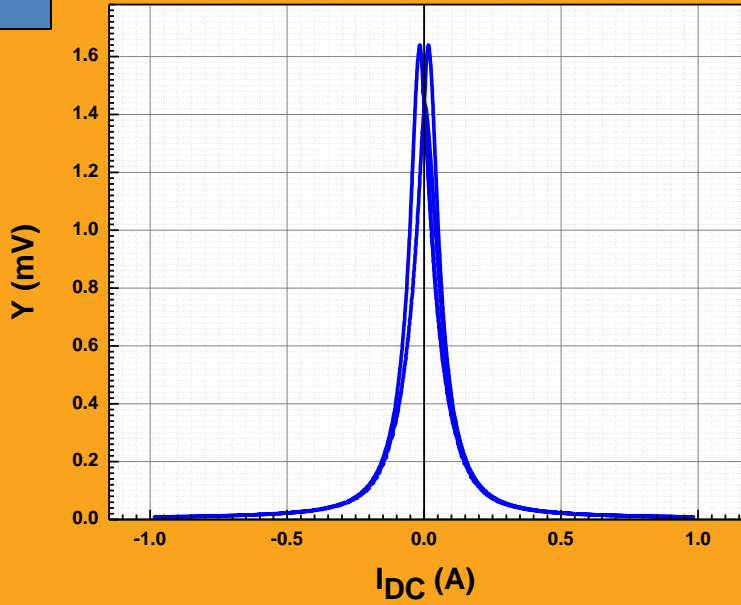
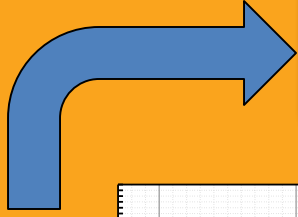


# From permeability to B-H hysteresis loop

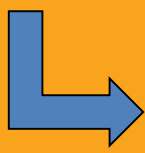
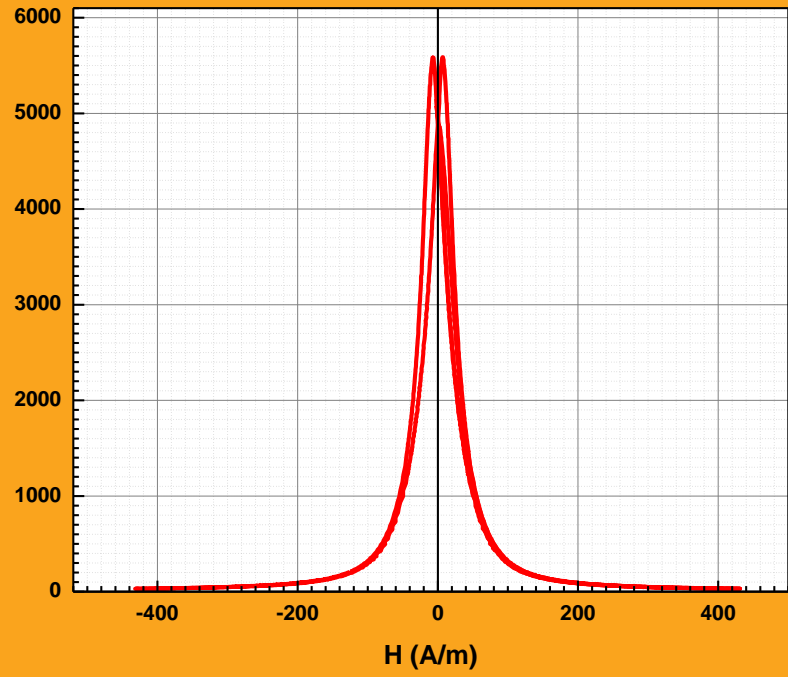
$$V_{lock-in} = \mu_r L_0 \frac{dI_p}{dt}$$

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

$\sim \omega !$



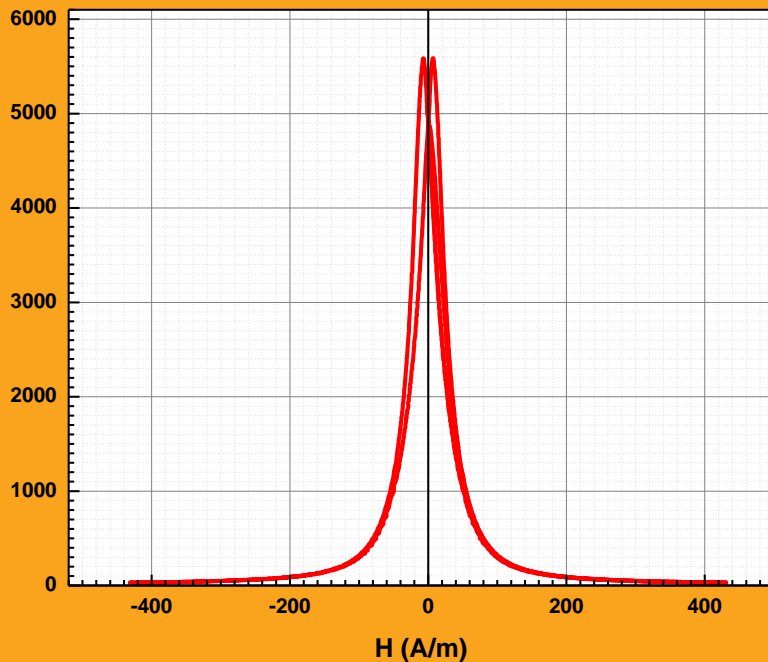
$\sim \omega$



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



# From permeability to B-H hysteresis loop

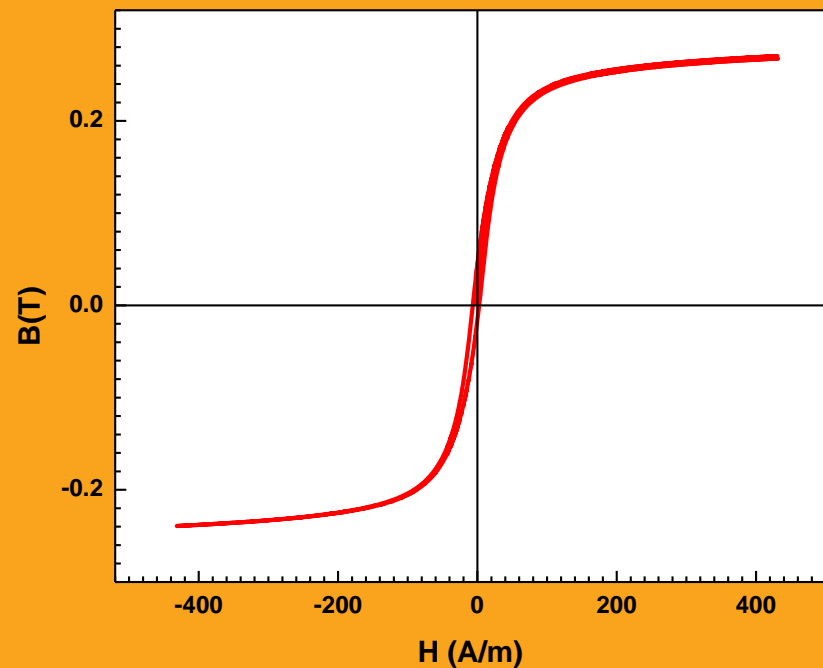


After integrating →

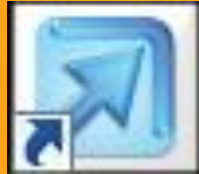
$$B(H) = \mu_0 \int \mu_r(H) dH$$

Step#4. From  $\mu_r(H)$  to B-H

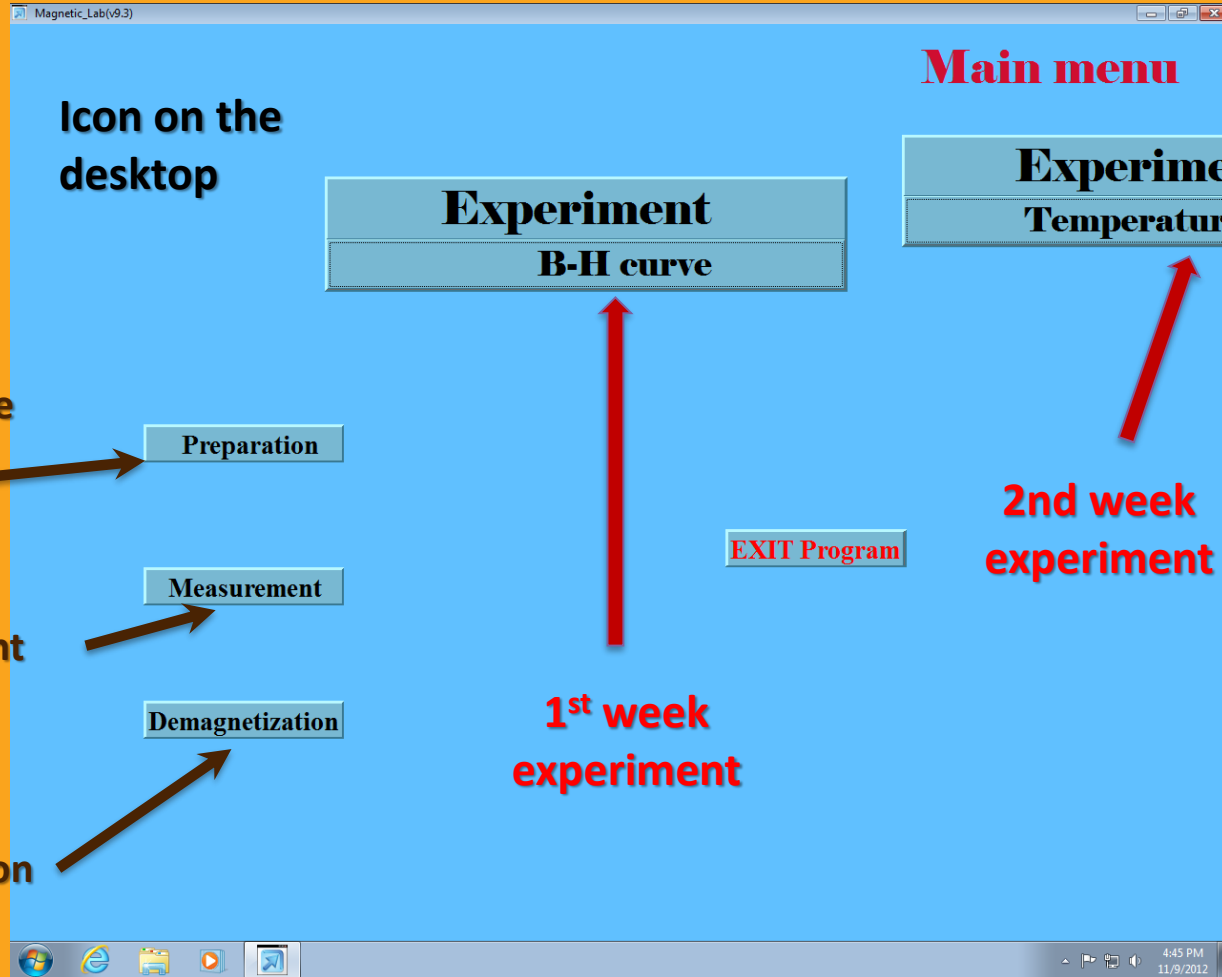
$$\mu(H_0) = \mu_0 \mu_r(H_0) = \left. \frac{dB}{dH} \right|_{H_0}$$



# Software issue



Magnetic Lab v9.2



Preparation of the profile of the experiment

B-H measurement

Demagnetization

Preparation

Measurement

Demagnetization

Experiment  
B-H curve

Main menu

Experiment  
Temperature scan

EXIT Program

2nd week  
experiment

1st week  
experiment



# Software issue

Measuring profile preparation. Using profile template

**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.

There is no saved parameters set or is damaged. Start to prepare new profile or open saved one.

Idc (A)

time (s.u)

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

Open a new file

Create a new file

Save file

Exit

Open a new file

Create a new file

Save prepared file for future use



# Software issue

Measuring profile preparation. Using profile template.

Enter File Name for T profile:

Name	Date modified	Type
Lecture#3. Lock-in and FFT	3/29/2016 3:25 PM	File folder
Lecture#4. Pulses in transmission lines	2/8/2016 1:20 PM	File folder
Lecture#5. Millikan Oil Drop Experiment	2/15/2016 12:48 PM	File folder
Lecture#6. Error analysis. Data fitting	2/22/2016 2:06 PM	File folder
Lecture#7. Torsional Oscillator	2/29/2016 1:39 PM	File folder
Lecture#8. Driven torsional Oscillator	3/7/2016 1:19 PM	File folder
Lecture#9. Microwaves 1	3/14/2016 3:02 PM	File folder
Lecture#10. Microwaves 2	3/28/2016 1:51 PM	File folder
Lecture#11. Hall probe	4/4/2016 1:42 PM	File folder
1.jpg	4/11/2016 1:43 PM	JPEG image
2.jpg	4/11/2016 1:43 PM	JPEG image
3.jpg	4/11/2016 1:45 PM	JPEG image
4.jpg	4/11/2016 1:47 PM	JPEG image
sl.par	4/11/2016 1:46 PM	PAR File

File name: sl.par

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

Step(A)

Step(A)
0: 0
100m
20m

Create a new file

Save file

Exit

**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.

Open a new file

Create a new file

Save file

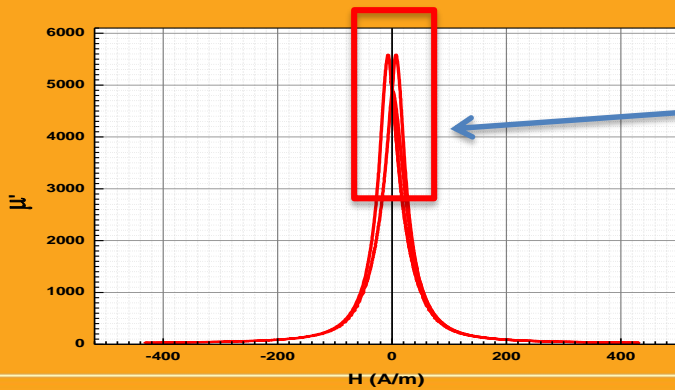
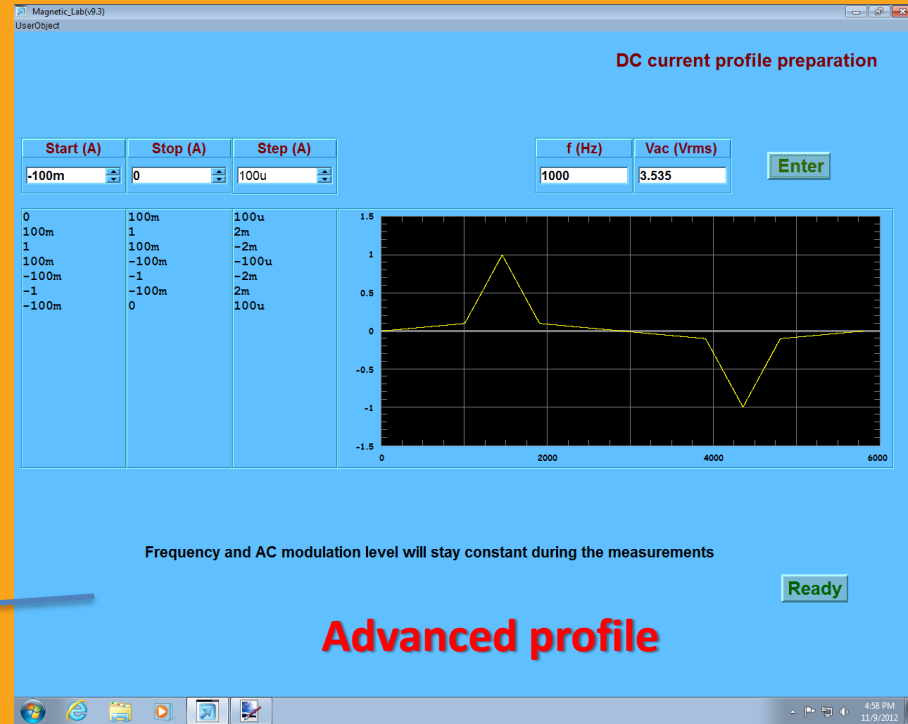
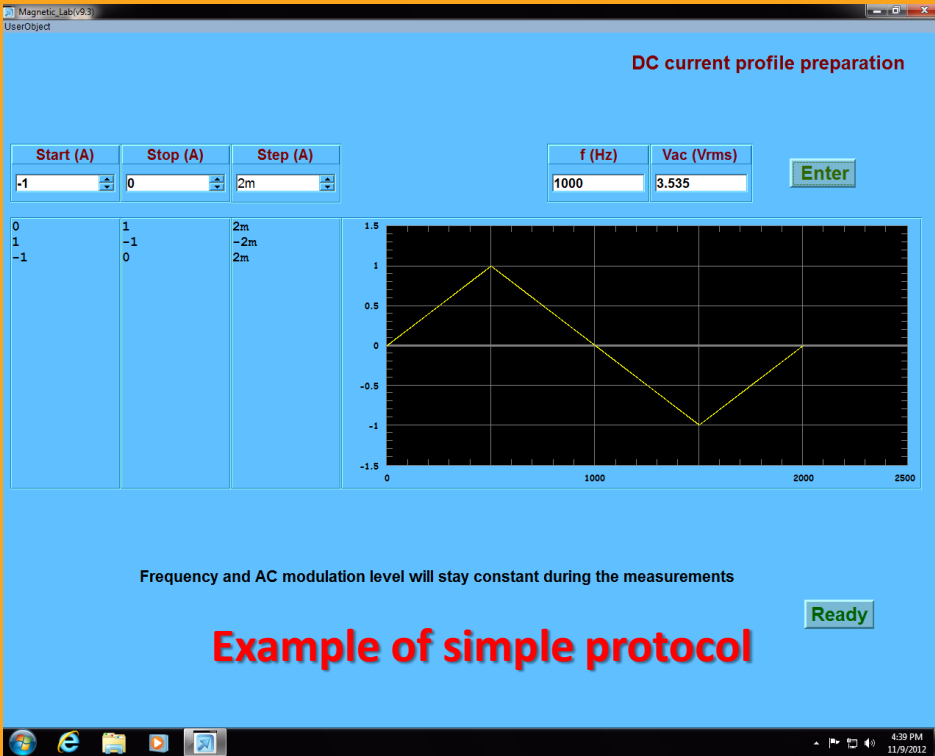
Exit

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

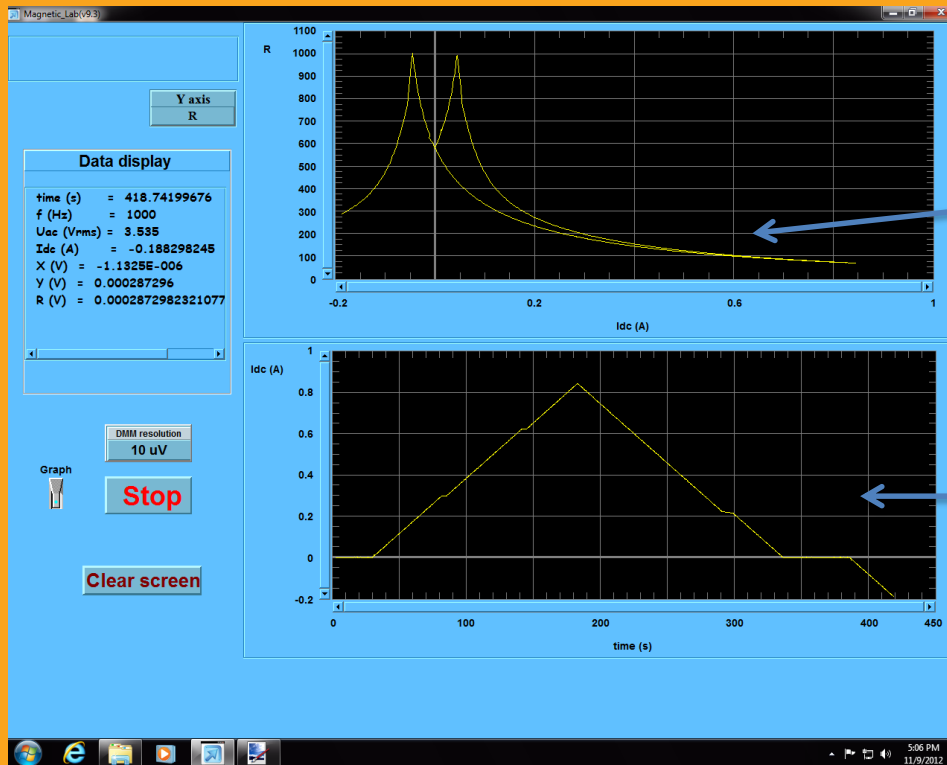


# Software issue

## 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	0.01624	-1.22025E-	7.56765E-	7.56865E-



# 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)	f(Hz(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-6	7.5676E-5	7.5686E-5				50.82553	0.82566	0.02883
8	15.141	1000	3.535	0.01739	-1.26661E-6	7.51545E-5	7.51652E-5				50.47528	0.85068	0.03092
9	15.484	1000	3.535	0.01974	-8.12117E-6	7.50502E-5	7.50546E-5				50.40523	0.54543	0.0351
10	15.875	1000	3.535	0.02174	-1.1772E-6	7.47894E-5	7.47987E-5				50.23007	0.79063	0.03865
11	16.328	1000	3.535	0.02263	-1.09524E-6	7.46031E-5	7.46111E-5				50.10494	0.73559	0.04025
12	16.703	1000	3.535	0.02589	-9.76033E-6	7.43424E-5	7.43488E-5				49.92985	0.65552	0.04605
13	17.063	1000	3.535	0.02698	-1.15485E-6	7.37687E-5	7.37777E-5				49.54454	0.77562	0.04798



Raw data

Parameters

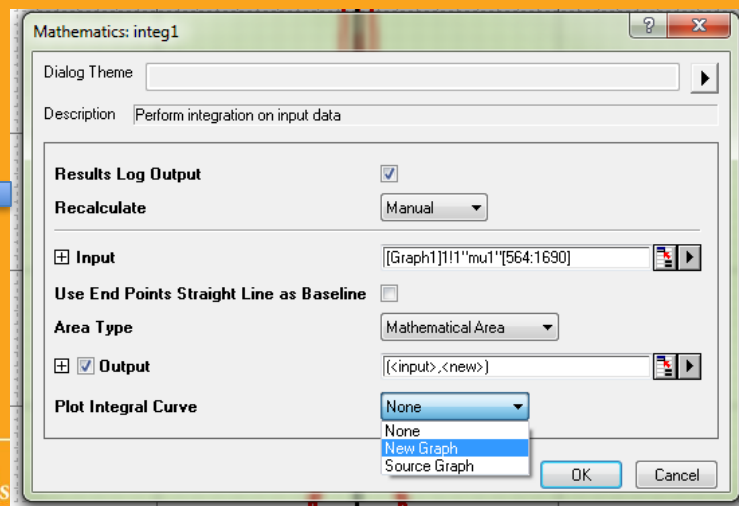
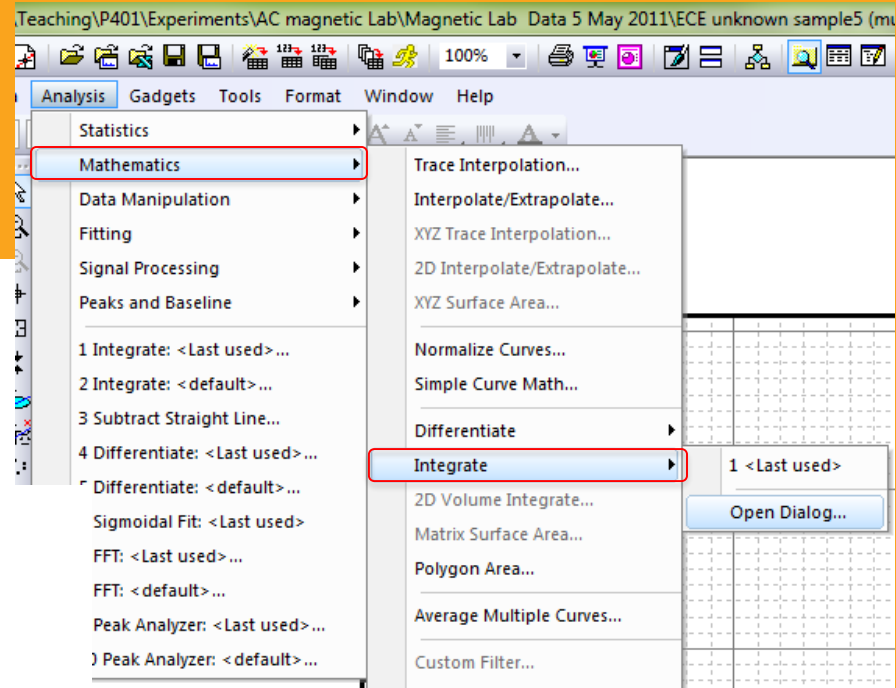
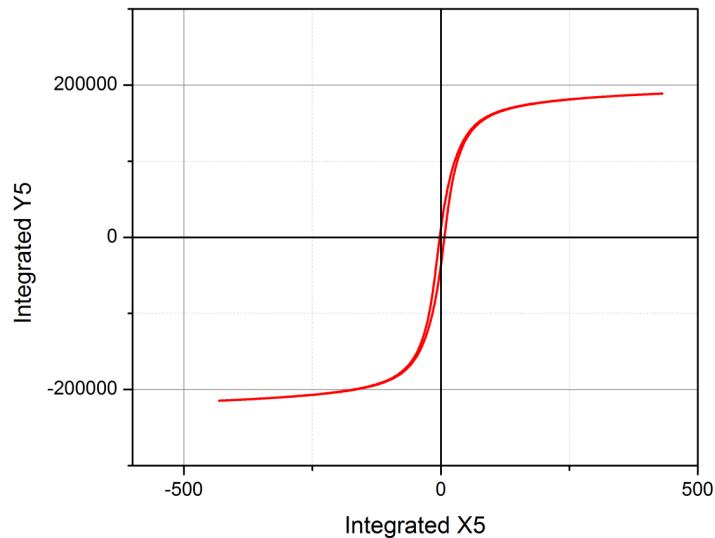
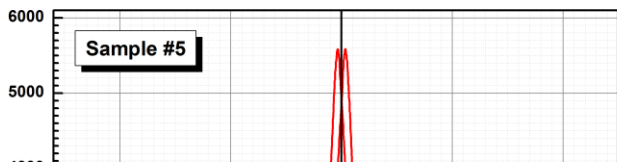
Calculated results





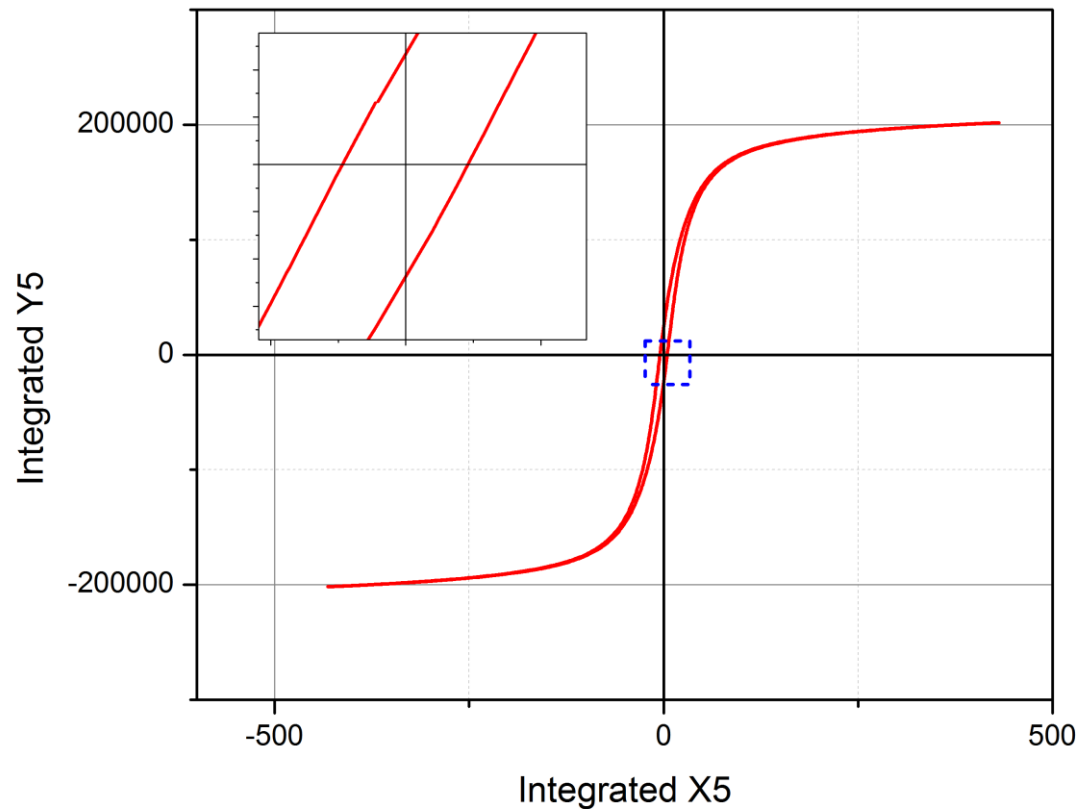
# Data analysis using Origin. Integrating.

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



# Data analysis using Origin. Integrating.

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



# 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**

