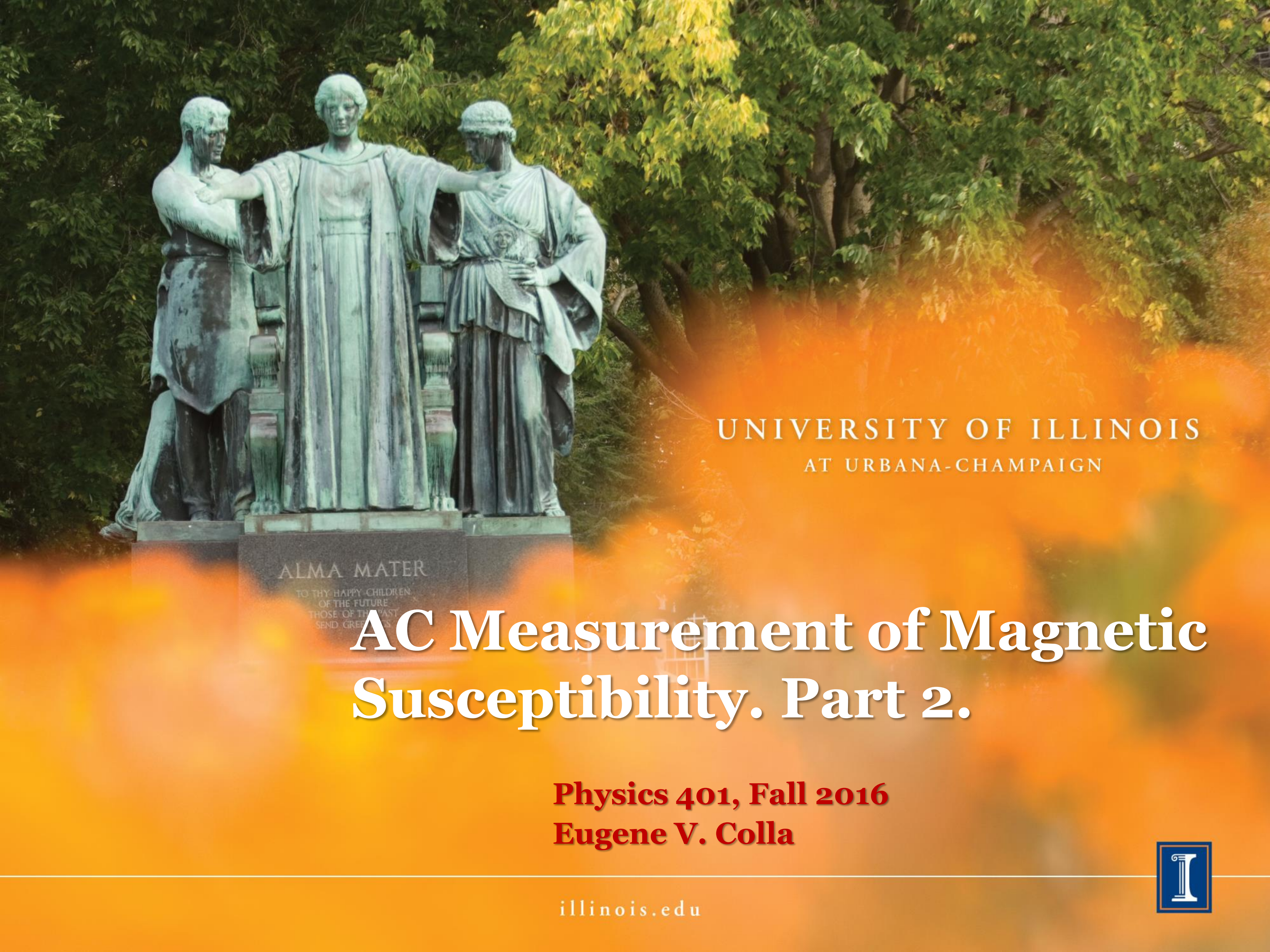


UNIVERSITY OF ILLINOIS
AT URBANA-CHAMPAIGN

AC Measurement of Magnetic Susceptibility. Part 2.

Physics 401, Fall 2016

Eugene V. Colla

Outline

- What and how we measuring (week1)
- Magnetic looses
- Temperature dependencies of permeability
- End of semester

Magnetic materials.

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

Magnetic induction

Permeability of free space

Magnetic field

Magnetization

$$M = \chi \bullet H$$

χ – magnetic susceptibility

Magnetic materials.

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

$$M = \chi \bullet H$$

In general χ is a function of H and T

$$M = \chi(H,T) \bullet H$$

$$\chi(H,T) = \left(\frac{\partial M}{\partial H} \right)_T$$

Magnetic materials.

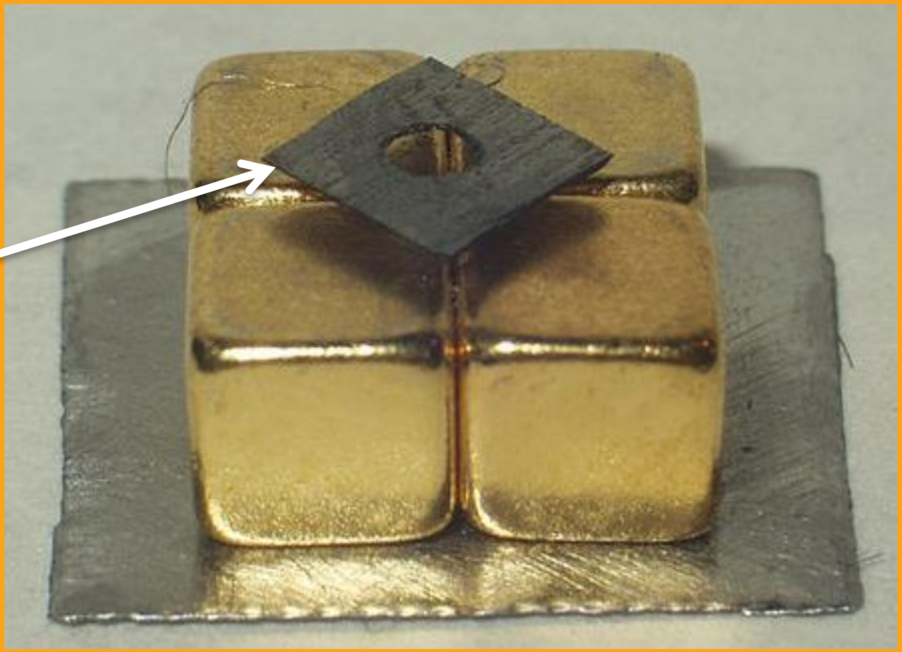
$$B = \mu_0 \left(H + \chi H \right) = \mu_0 \left(1 + \chi \right) H = \mu_0 \mu_r H;$$
$$\mu_r = 1 + \chi$$

$\chi < 0$	-	**diamagnetics,**	$\mu_r < 1$
$\chi > 0$	-	**paramagnetics**	$\mu_r > 1$
$\chi >> 0$	-	**ferromagnetics**	$\mu_r >> 1$

Magnetic materials. Diamagnetism.

Material	χ_v (10^{-5})
Bismuth	−16.6
Carbon (diamond)	−2.1
Carbon (graphite)	−1.6
Copper	−1.0
Lead	−1.8
Mercury	−2.9
Pyrolytic carbon	**−40.0**
Silver	−2.6
Superconductor	-10^5
Water	−0.91

$\chi < 0$ - diamagnetics

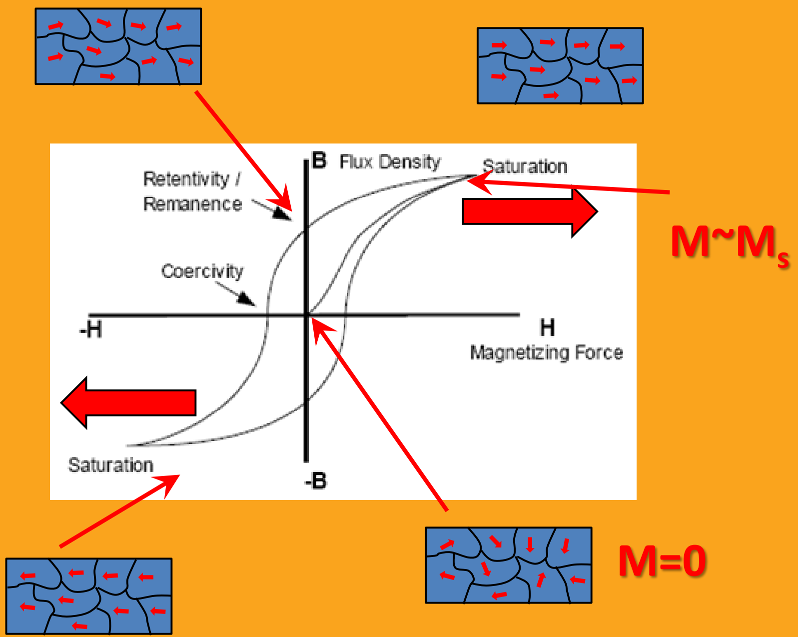


Levitation of the pyrolytic carbon

Ideal diamagnetic $\chi = -1$

Courtesy of Wikipedia

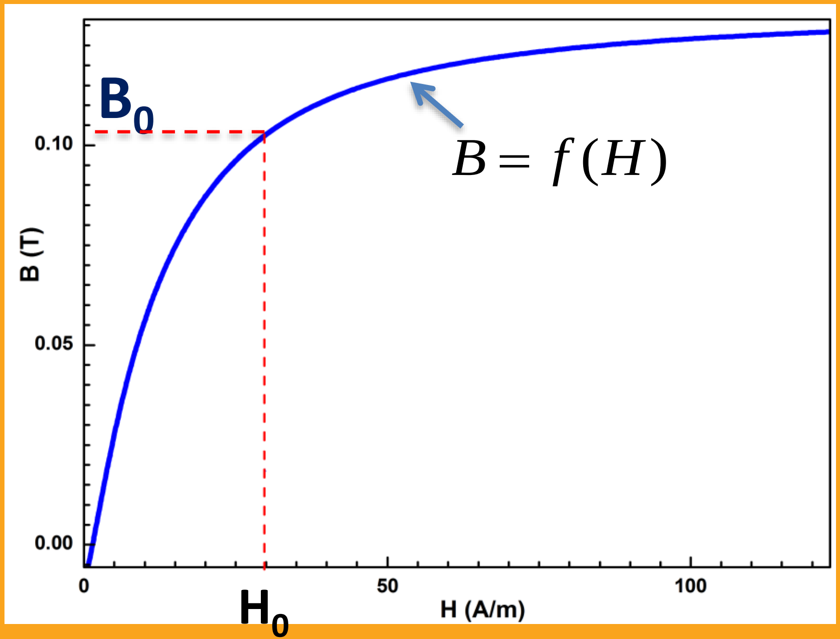
Magnetic materials. Ferromagnetism.



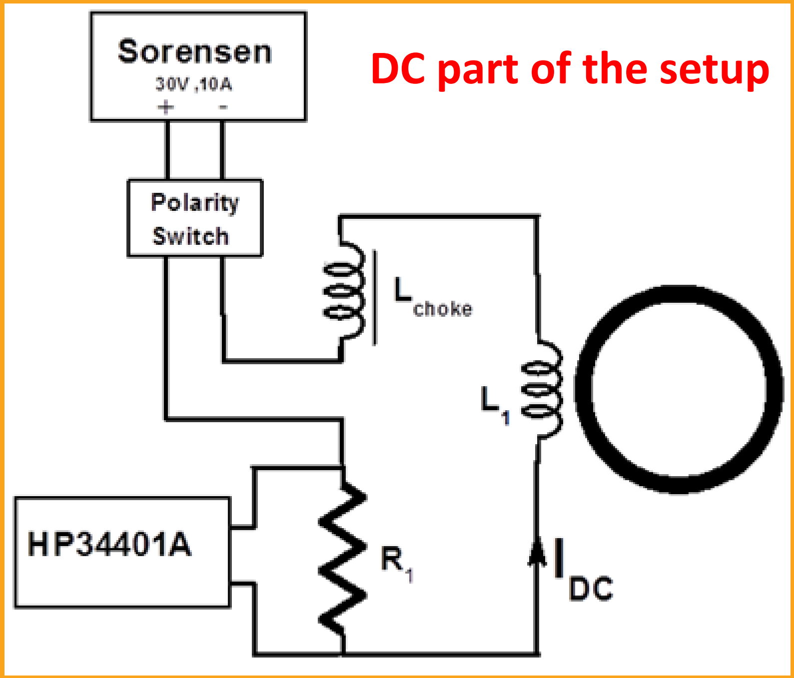
$\chi >> 1$ - ferromagnetics

Material	μ_r	B_{rem} (T)
Fe, 99.8% pure	5000	1.3
Permalloy	100,000	0.7
Superpermalloy	1,000,000	0.7
Co, 99% pure	250	0.5
Ni, 99% pure	600	0.4

Measuring of the permeability. DC field.



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



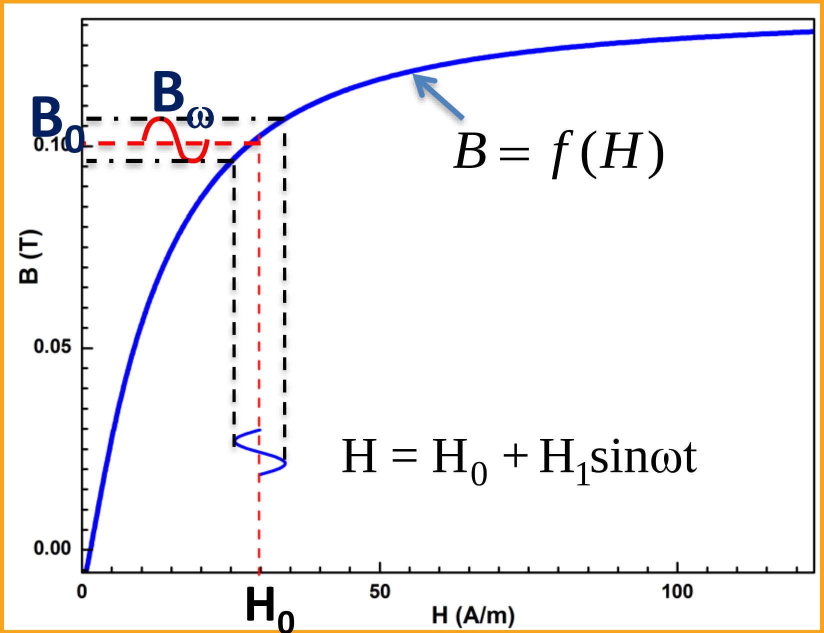
DC part of the setup

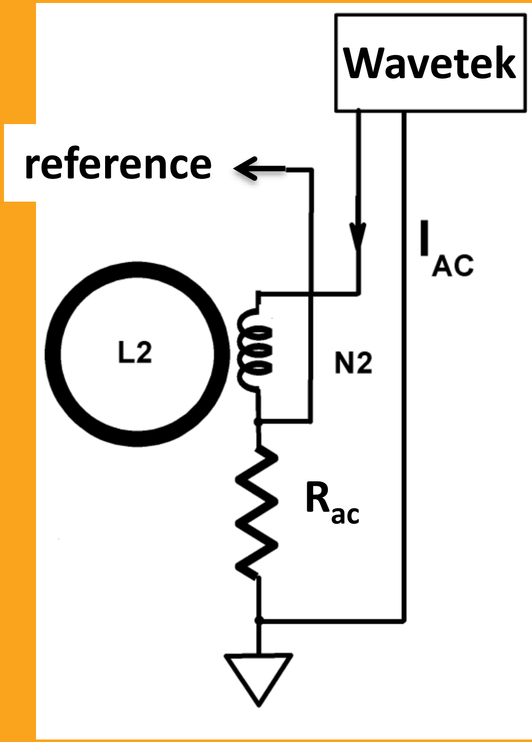
$$H_0 = \frac{N_p I_{DC}}{2\pi r}$$

Here Np – number of turns in DC primary coil

Measuring of the permeability. AC modulation

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





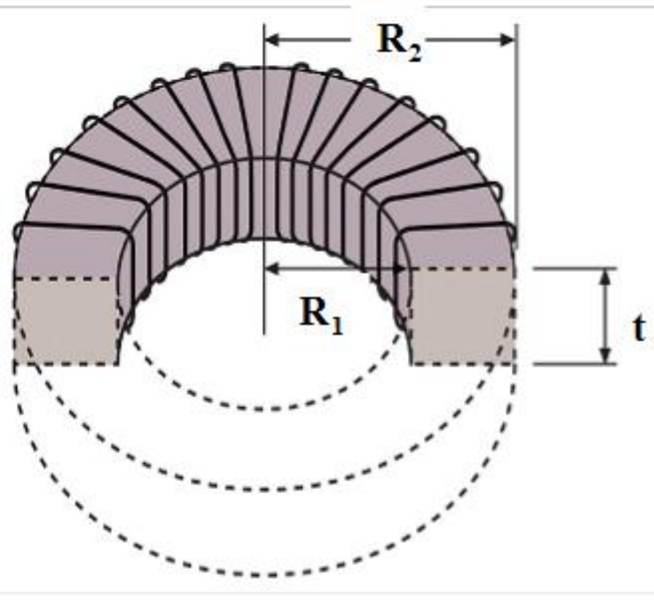
$$H_1 = \frac{N_p I_{AC}}{2\pi r}$$

$$B_\omega \sim \frac{df}{dH} = \frac{dB}{dH} = \mu = \mu_0 \mu_r$$

Here Np – number of turns in AC primary coil

Measuring of the permeability. AC modulation

Primary coil of N_p turns supplied by current I_p creates magnetic field H and flux Φ



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

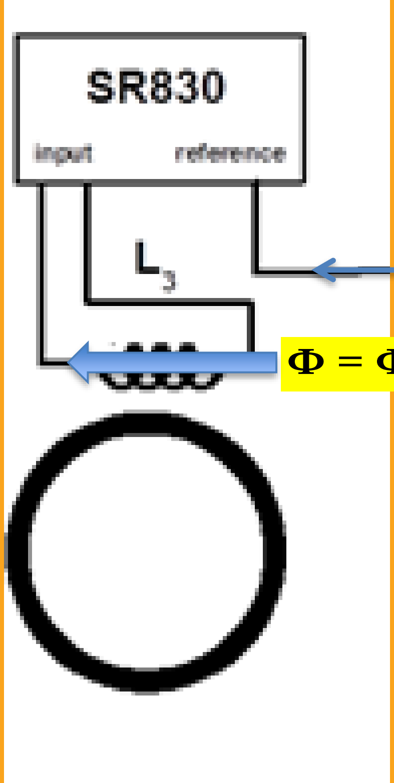
$R_2 < r < R_1$

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

da=dr*t

Measuring of the permeability. Pickup coil.

Lock-in measures emf on the pickup coil



$$\Phi = \Phi_0 + \Phi_1 \cos\omega t$$

$$V_{lock-in} = -N_{pickup}\frac{d\Phi}{dt}$$

Faraday's law

$$\Phi_1 = \mu\int \vec{H}_{ac}\cdot d\vec{a} = \frac{\mu\, I_{AC}\, N\, t}{2\pi}\int_{R_1}^{R_2}\frac{dr}{r} = \frac{\mu\, I\, N\, t}{2\pi}\ln\frac{R_2}{R_1}$$

This is per 1 turn of the pickup coil !

Here I_{AC} is ac current in primary coil L3; $I_{AC} = \frac{V_0 \sin(\omega t)}{R_{ac}}$

$$V_{lock-in} = N_{pickup}\frac{\mu\, N\, t}{2\pi}\ln\frac{R_2}{R_1}\frac{dI_{AC}}{dt} = N_{pickup}\frac{\mu\, N\, t}{2\pi}\ln\frac{R_2}{R_1}\frac{V_{AC}}{R_{ac}}\omega\cos(\omega t) =$$

$$= \mu_r L_0 \frac{V_{AC}}{R_{ac}}\omega\cos(\omega t); \qquad \text{where } L_0 = N_{pickup}\frac{\mu_0\, N\, t}{2\pi}\ln\frac{R_2}{R_1}$$

Measuring of the permeability. Pickup coil.

$$V_{lock-in} = N_{pickup}\frac{\mu N t}{2\pi}\ln\frac{R_2}{R_1}\frac{dI_{AC}}{dt} = N_{pickup}\frac{\mu N t}{2\pi}\ln\frac{R_2}{R_1}\frac{V_{AC}}{R_{ac}}\omega\cos(\omega t) =$$

$$= \mu_r L_0 \frac{V_{AC}}{R_{ac}}\omega\cos(\omega t); \qquad \text{where } L_0 = N_{pickup}\frac{\mu_0 N t}{2\pi}\ln\frac{R_2}{R_1}$$

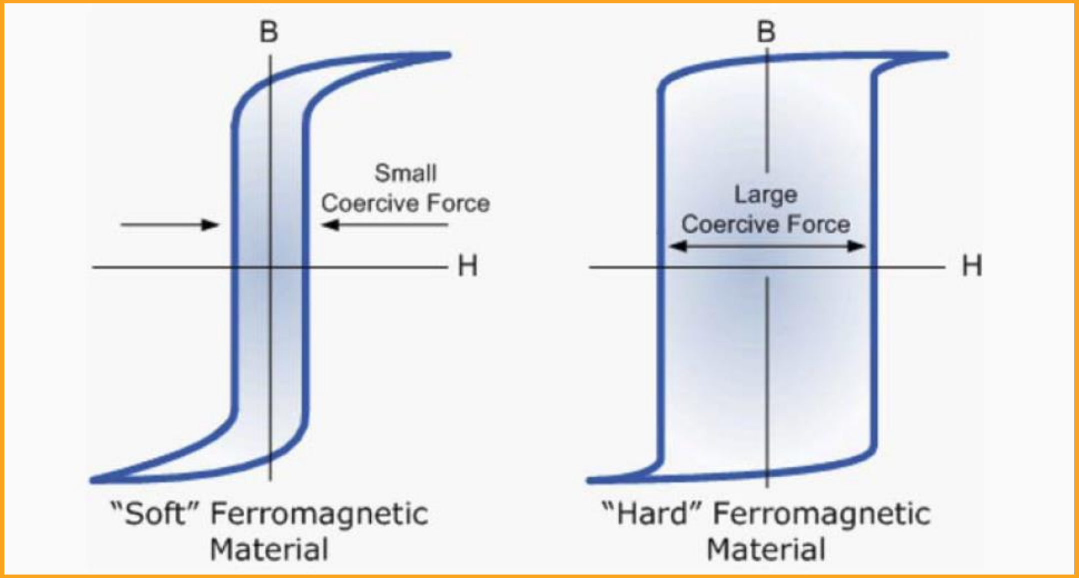
Geometry of toroid

Resistor in AC current loop

In general $\mu_r = \mu' - j\mu''$

Because of $\pi/2$ phase shift ($\cos(\omega t)$) the "μ'" signal will be delivered to Y channel of the lock-in amplifier. μ'' provides the information about the losses in system

Hysteresis Loops. Remagnetization loses



Energy of the magnetic field

$$W = V \int H dB$$

By cycling around the loop

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

V here is a volume of the magnetic material

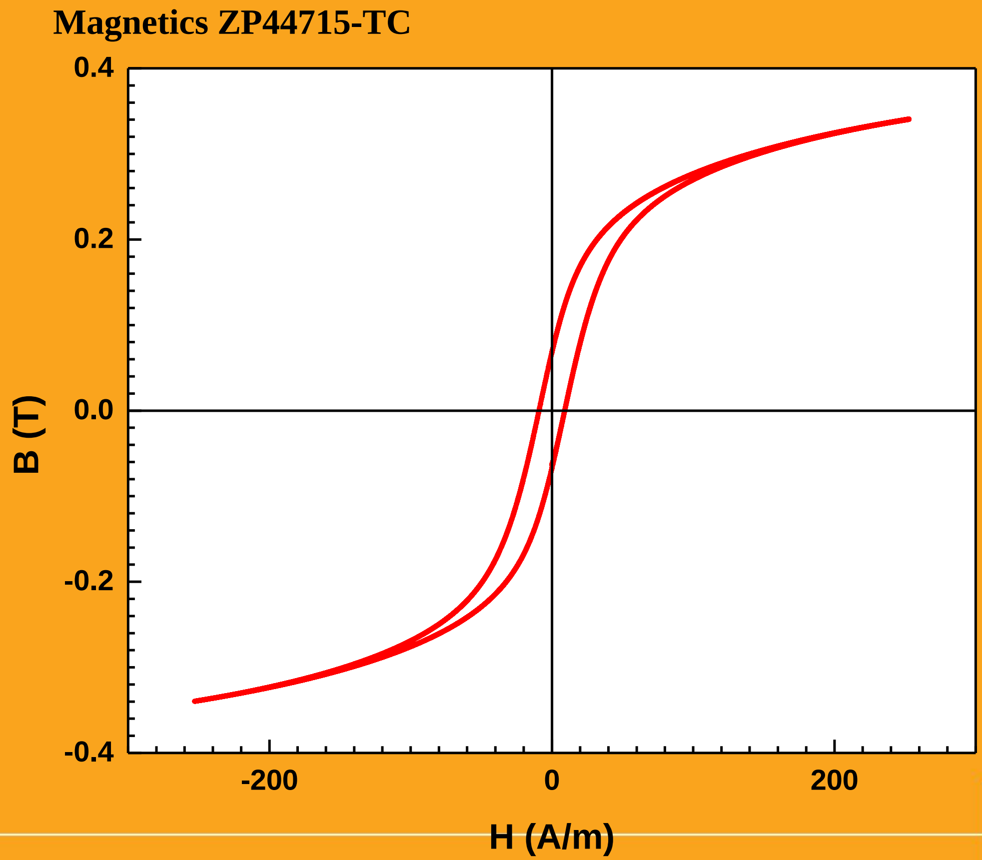
Calculating of the magnetic induction B

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

$$\mu = \mu_0 \mu_r = \frac{dB}{dH}; \quad B = \mu_0 \int \mu_r (H) dH$$

Magnetics ZP44715-TC

After integrating

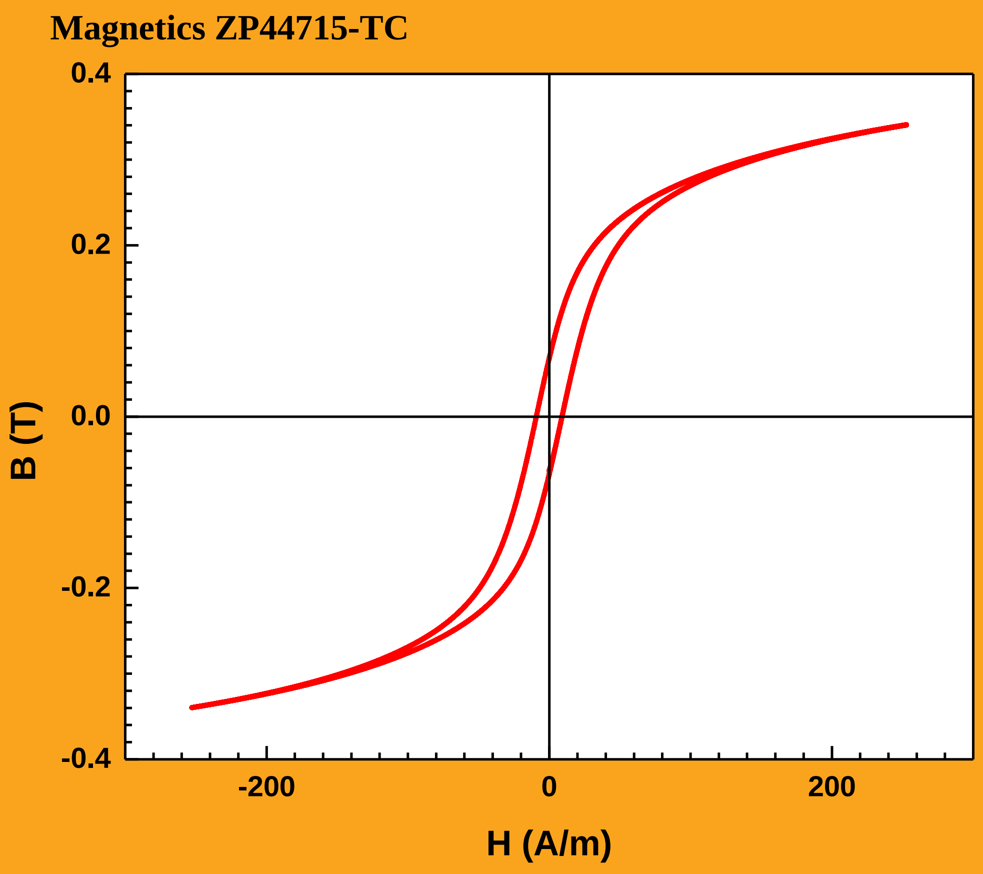


Hysteresis Loops. Remagnetization loses

$$W = V \int HdB$$

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

Using Origin Pro for integrating



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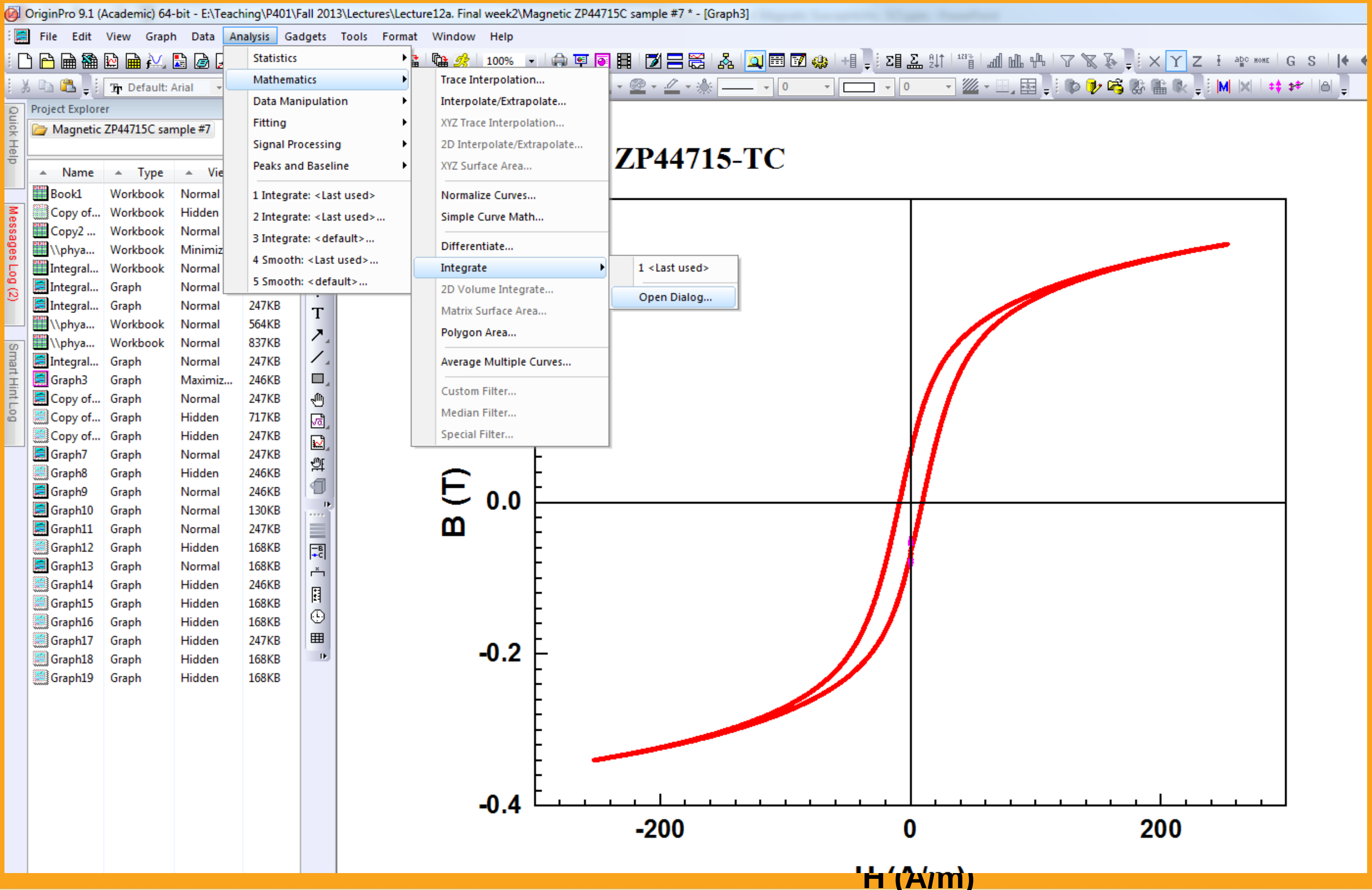

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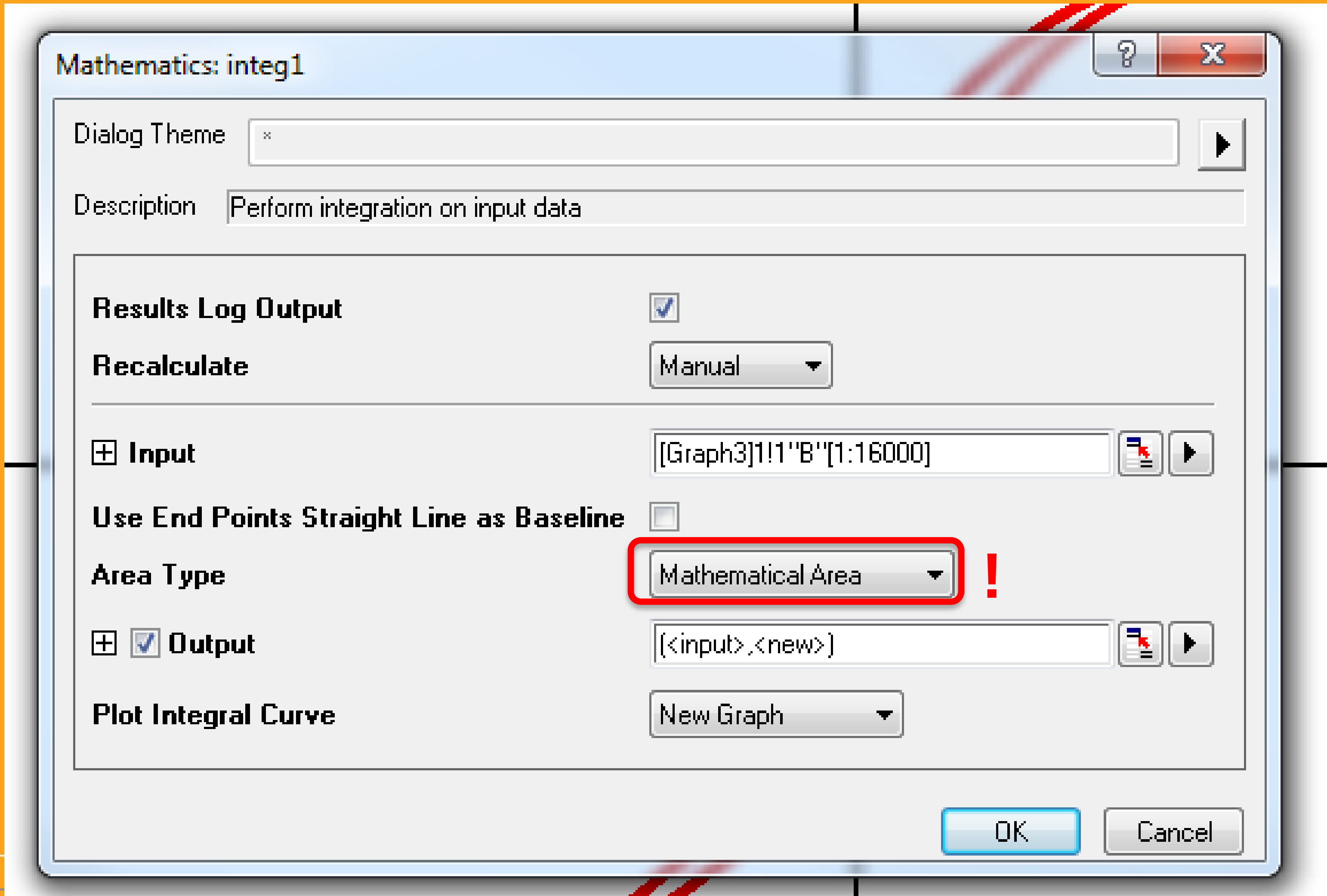

Hysteresis Loops. Remagnetization loses

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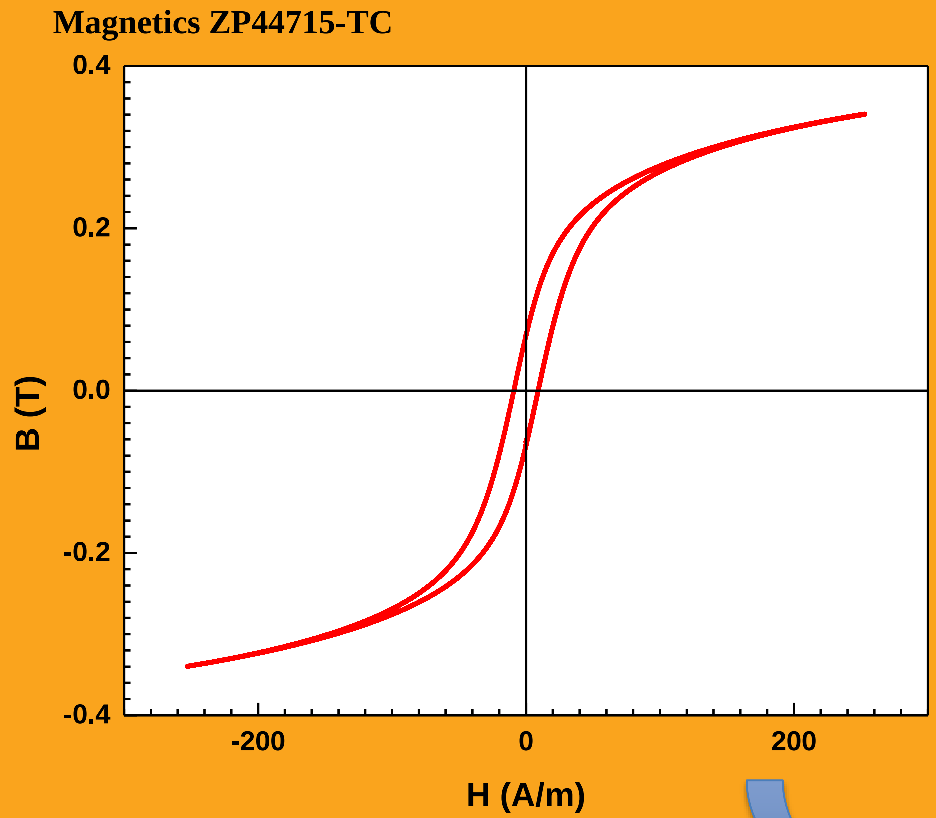
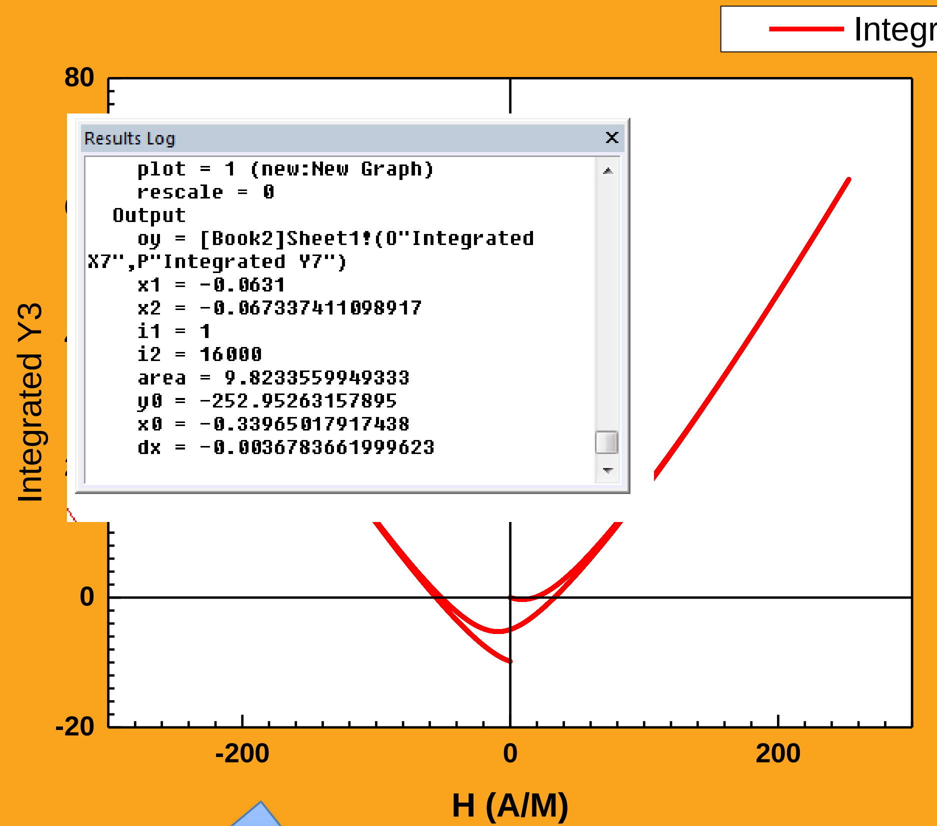
Using Origin Pro for integrating





Hysteresis Loops. Remagnetization loses

$$W = V\int HdB$$

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

Using Origin Pro for integrating

```
Results Log
    plot = 1 (new:New Graph)
    rescale = 0
  Output
    oy = [Book2]Sheet1!(O"Integrated
X7",P"Integrated Y7")
    x1 = -0.0631
    x2 = -0.067337411098917
    i1 = 1
    i2 = 16000
    area = 9.8233559949333
    y0 = -252.95263157895
    x0 = -0.33965017917438
    dx = -0.0036783661999623
```

Units :

$$V(volume) \rightarrow m^3$$

$$H(field) \rightarrow A \bullet m^{-1}$$

$$B(magn.induction) \rightarrow kg \bullet s^{-2} \bullet A^{-1}$$

$$[V \bullet B \bullet H] \rightarrow m^2 \bullet kg \bullet s^{-2} \equiv J(\text{joule})$$

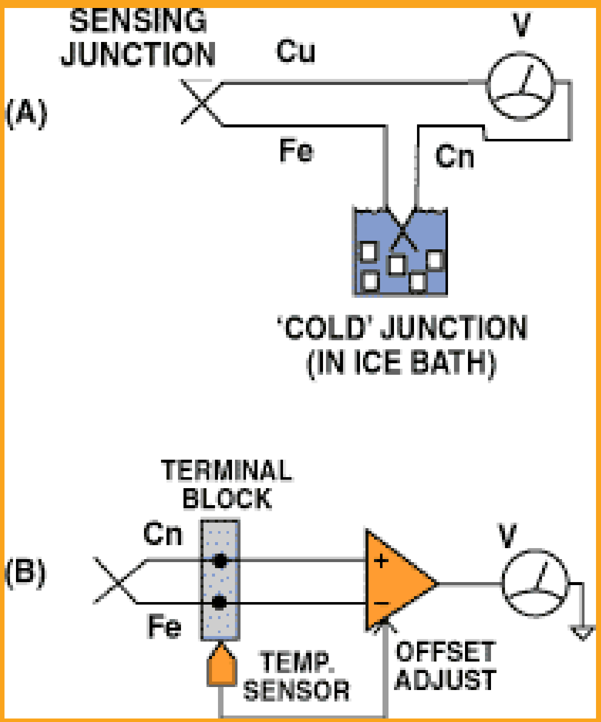
Power of loses: W/T = W*f, where T is period and f frequency

Temperature dependence of the magnetic permeability.

In this experiment we will measure permeability as a function of T. I_{DC} will be fixed. The default option I_{DC} =0.

DMM will measure the emf of T-type thermocouple.

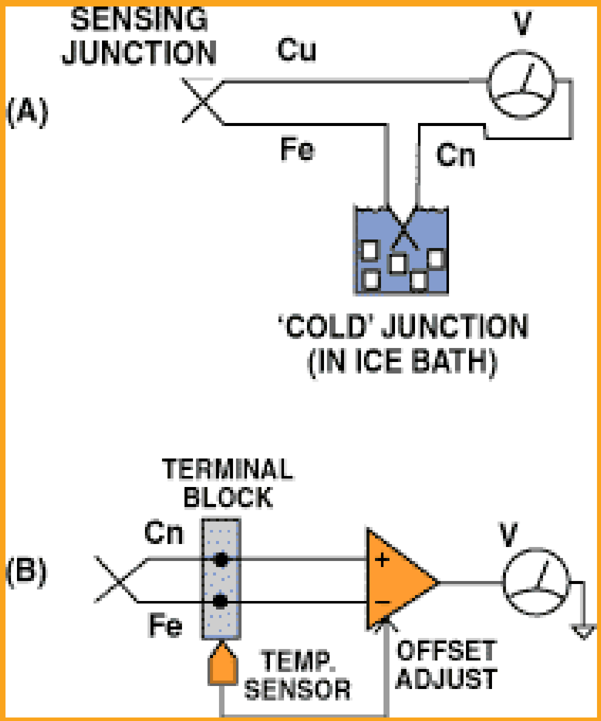
Measuring of the temperature. Thermocouple.

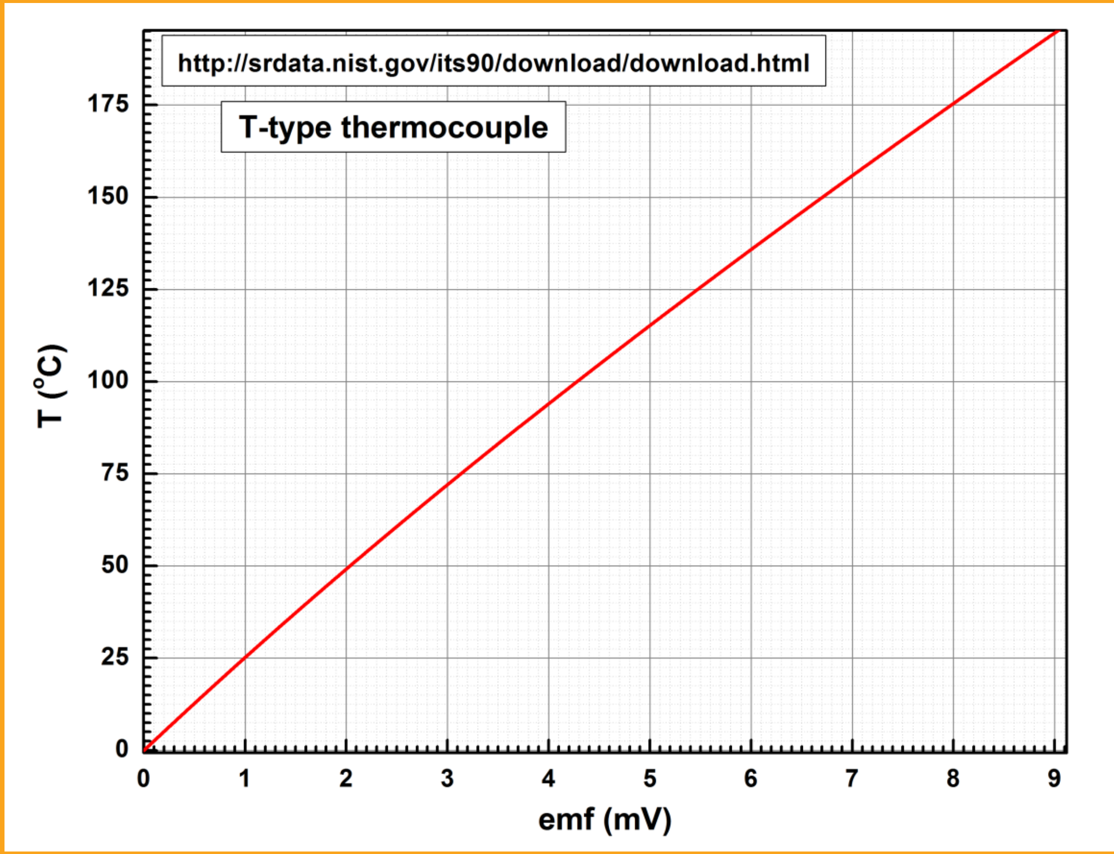


Type	Names of Materials	T Range
B	Platinum30% Rhodium (+) Platinum 6% Rhodium (-)	2500 -3100F 1370-1700C
C	W5Re Tungsten 5% Rhenium (+) W26Re Tungsten 26% Rhenium (-)	3000-4200F 1650-2315C
E	Chromel (+) Constantan (-)	200-1650F 95-900C
J	Iron (+) Constantan (-)	200-1400F 95-760C
K	Chromel (+) Alumel (-)	200-2300F 95-1260C
N	Nicrosil (+) Nisil (-)	1200-2300F 650-1260C
R	Platinum 13% Rhodium (+) Platinum (-)	1600-2640F 870-1450C
S	Platinum 10% Rhodium (+) Platinum (-)	1800-2640F 980-1450C
T	Copper (+) Constantan (-)	-330-660F -200-350C

Type T (copper-constantan) has thermoemf at 0°C 41.5μV/°C;

Measuring of the temperature. Thermocouple.

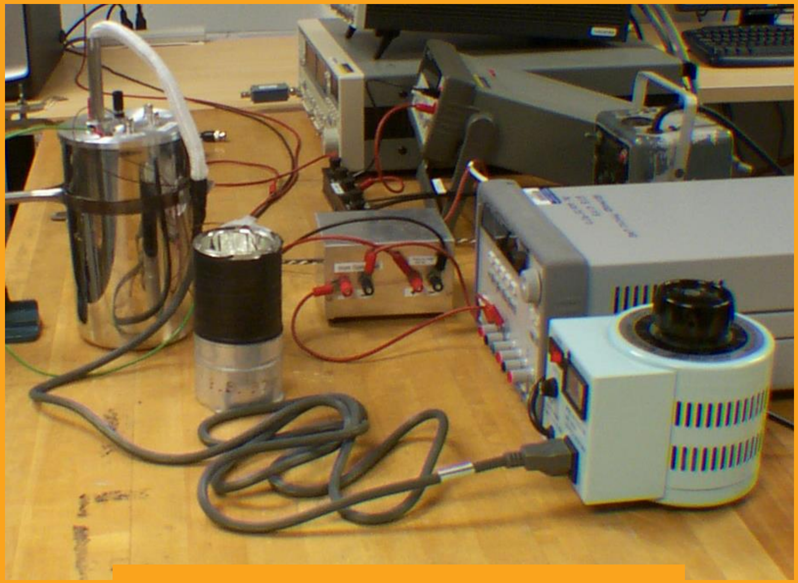




Type T (copper-constantan) has thermoemf at 0°C 41.5μV/°C;

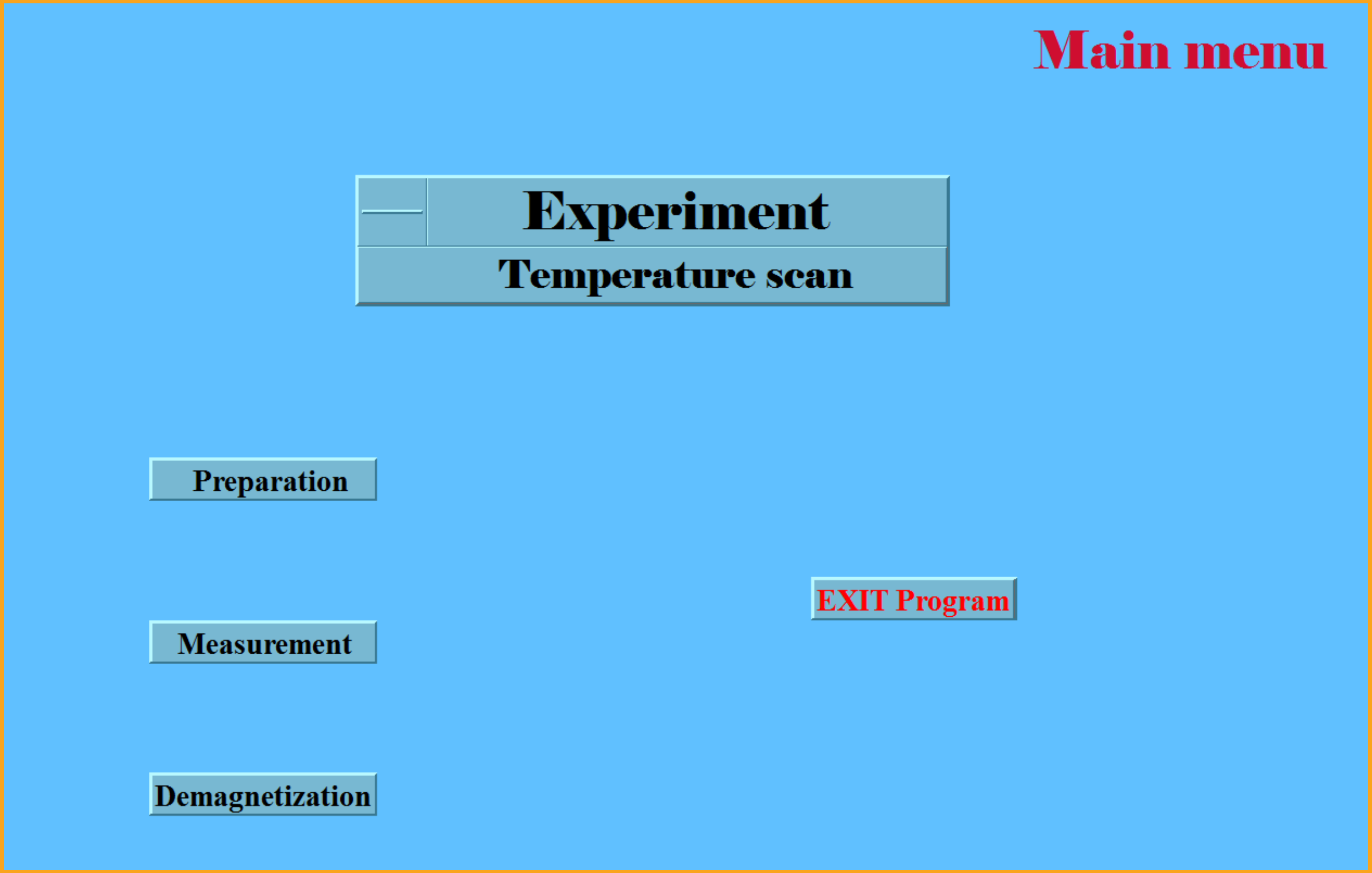
Measuring of the temperature. Temperature ramp.

Option 1: manual by changing the voltage applied to the heater

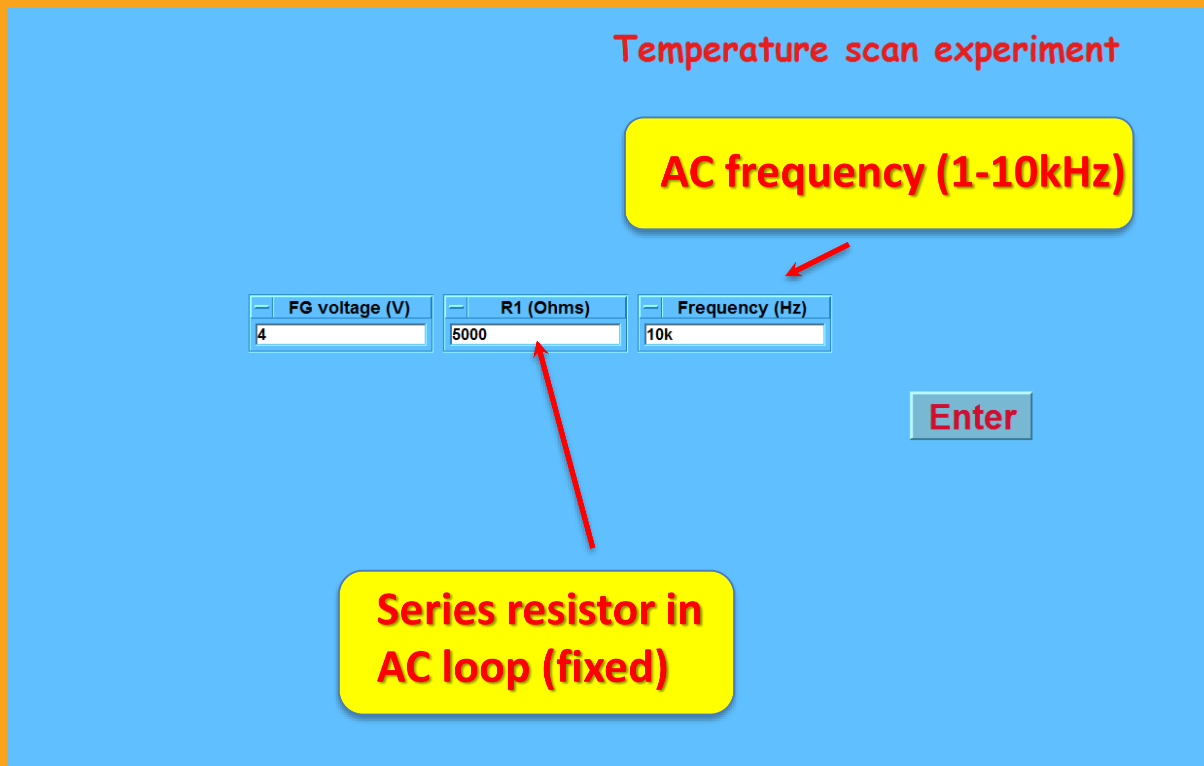


Option 2: by using Omega PID temperature controller

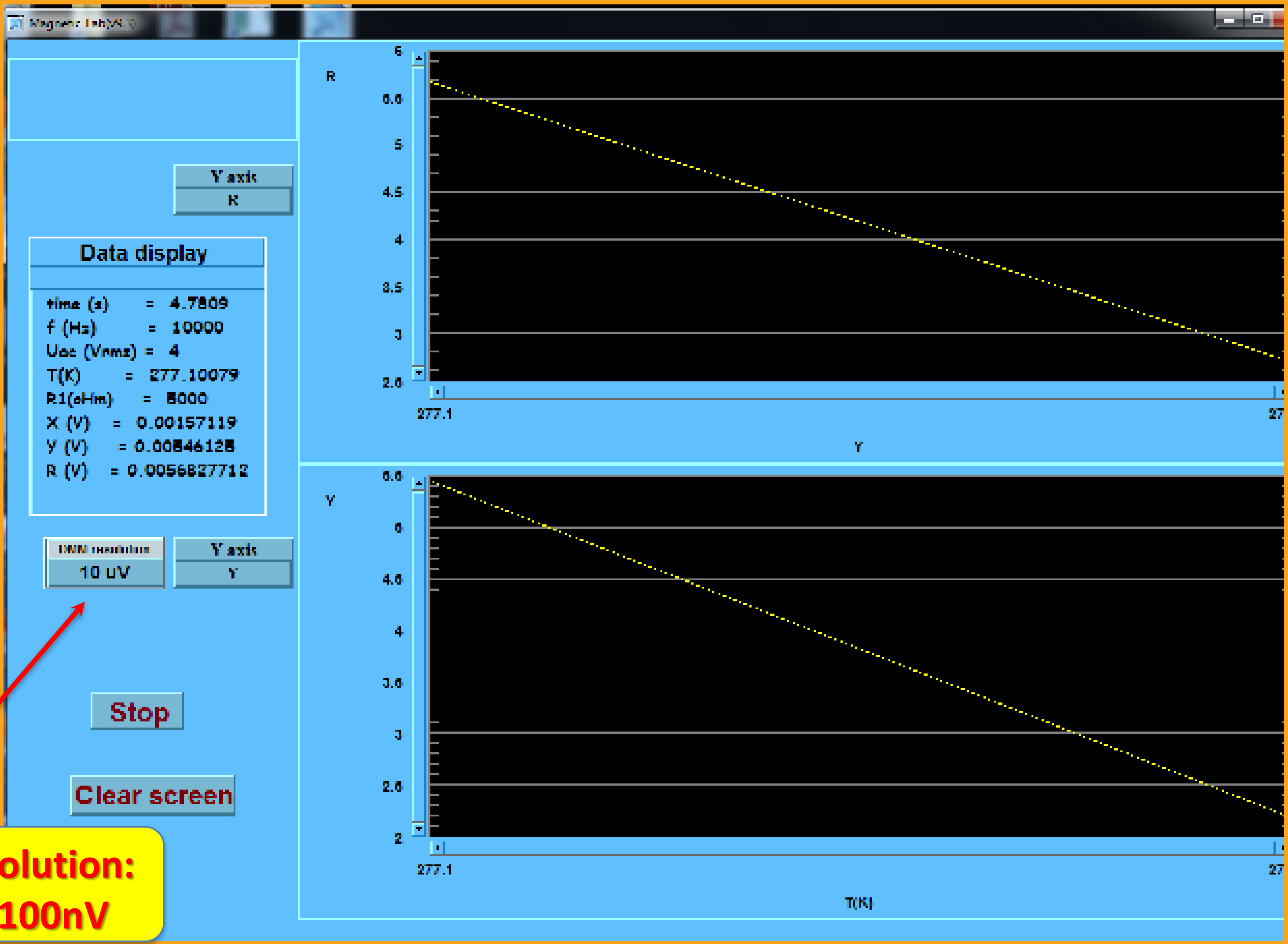
Measuring of the temperature. Software.



Measuring of the temperature. Software.



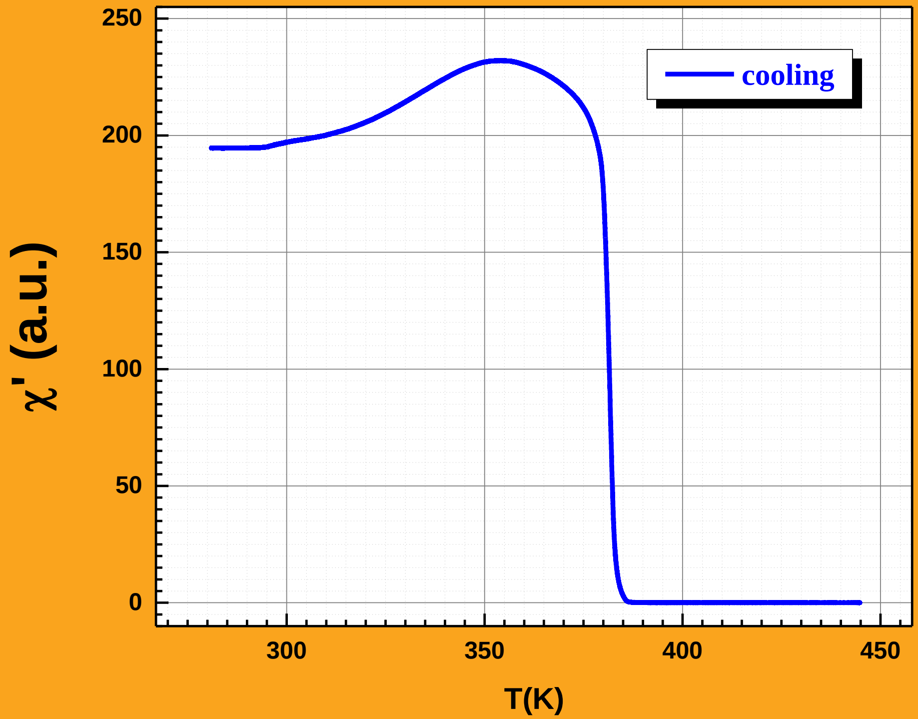
Measuring of the temperature. Software.



DMM resolution:
Optimal=100nV

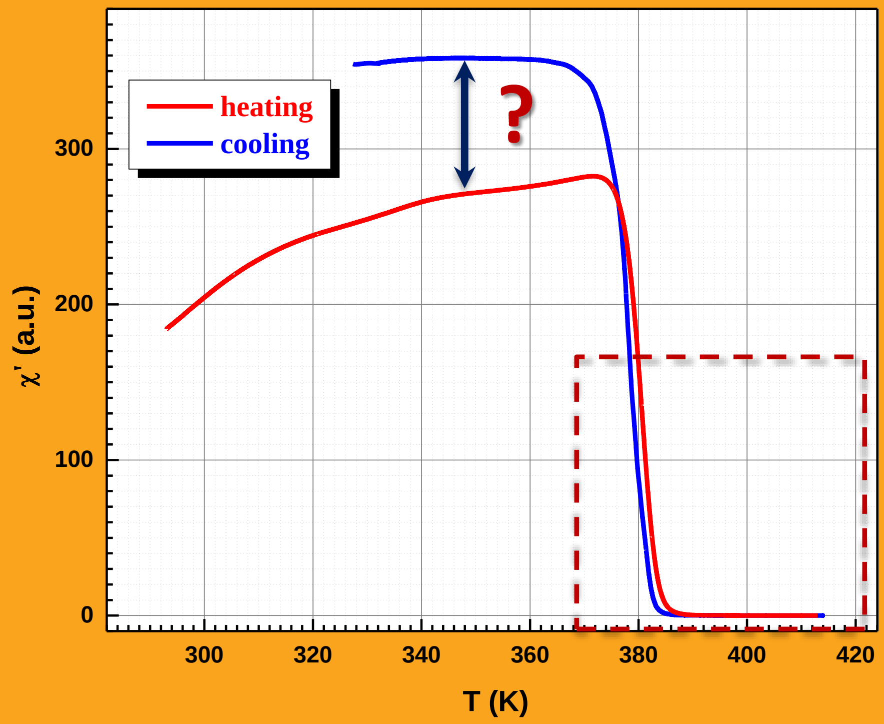
Temperature dependence of the magnetic permeability.

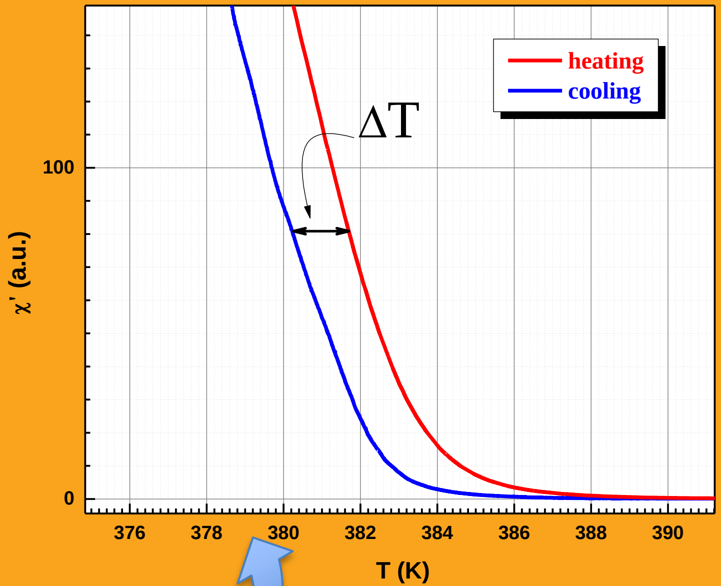
Ferroxcube 3E8



Temperature dependence of the magnetic permeability.

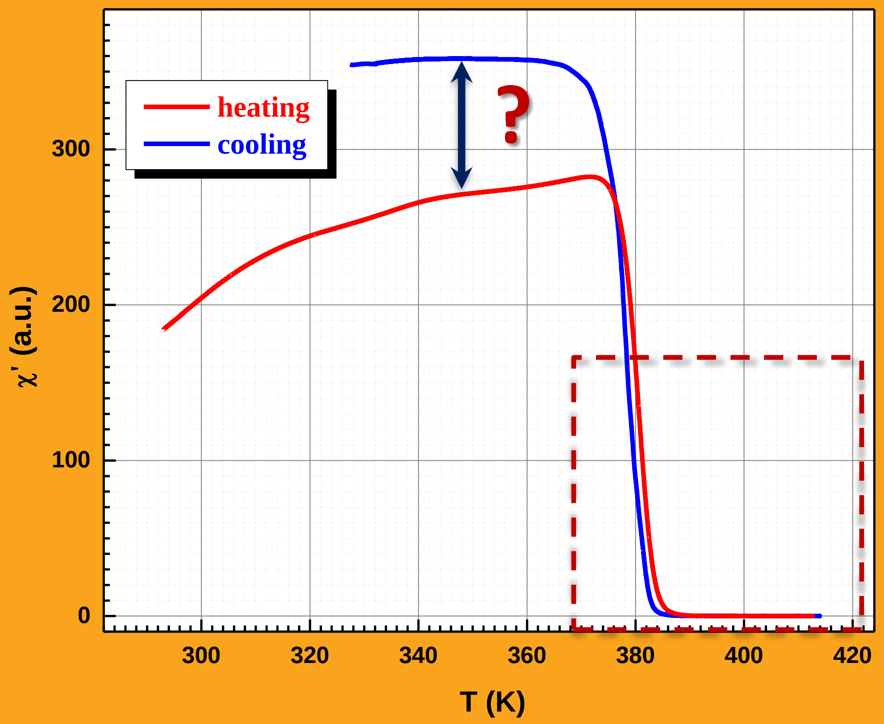
Ferroxcube 4A20



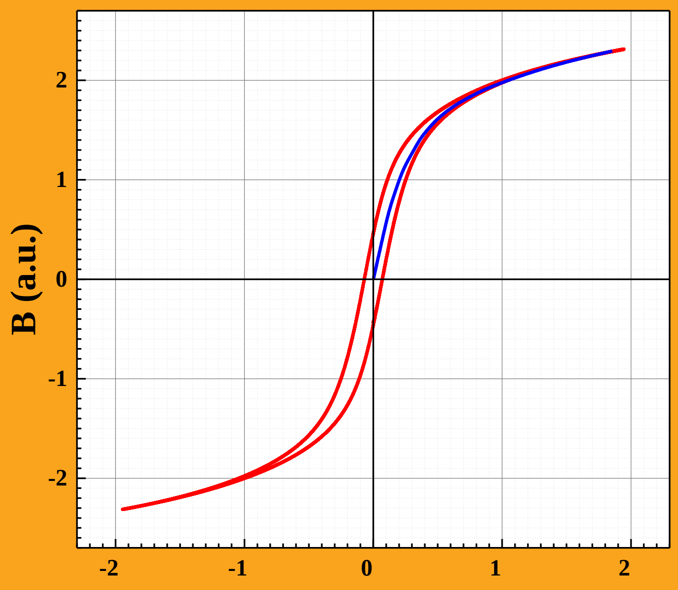


Hysteresis. Where it is coming from?

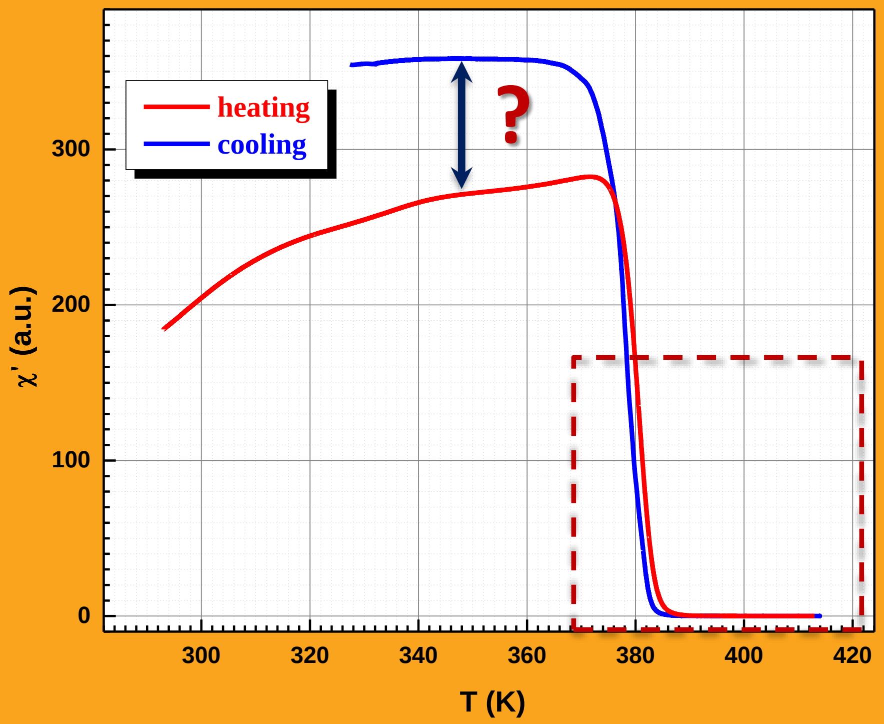
Temperature dependence of the magnetic permeability.



$$\mu(T) = \mu_0 \mu_r(T) = \frac{dB}{dH}(T)$$



Temperature dependence of the magnetic permeability.



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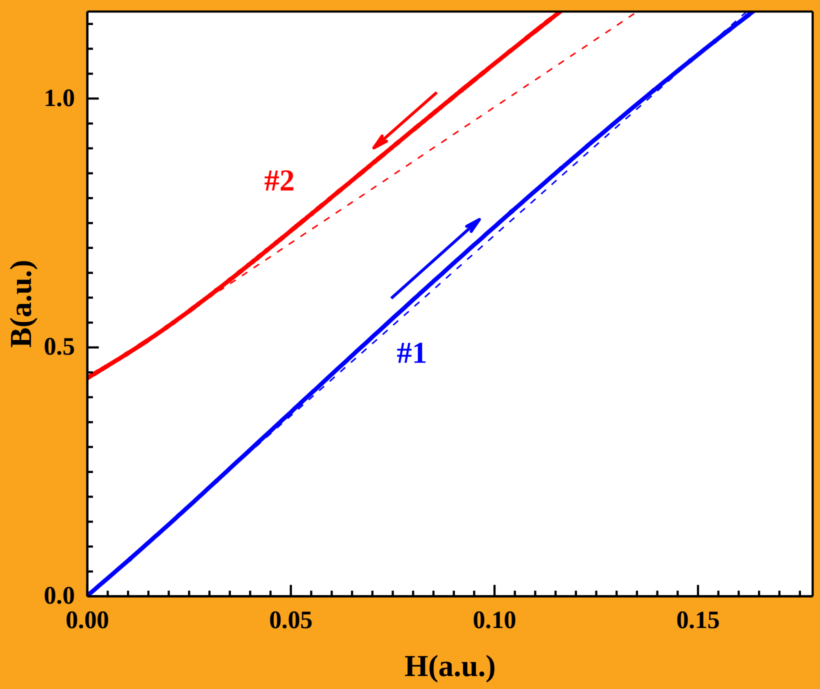
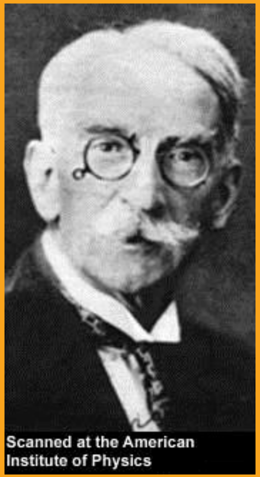


Slope#1 ~0.728

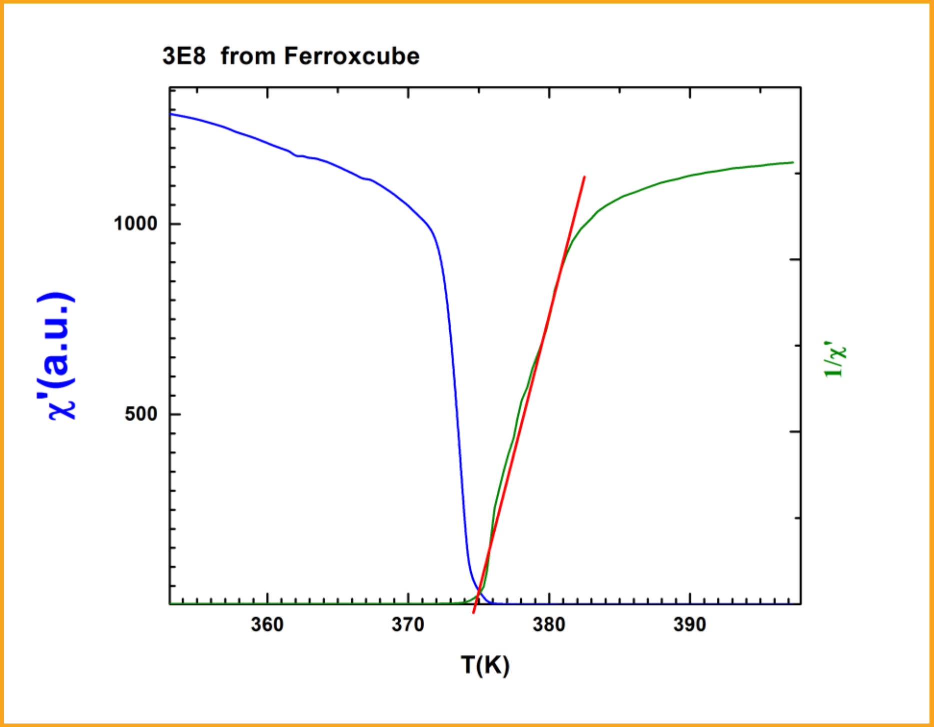
Slope#2 ~0.546

Temperature dependence of the magnetic permeability. Curie-Weiss law.

Pierre Curie
5.15.1859-4.19.1906



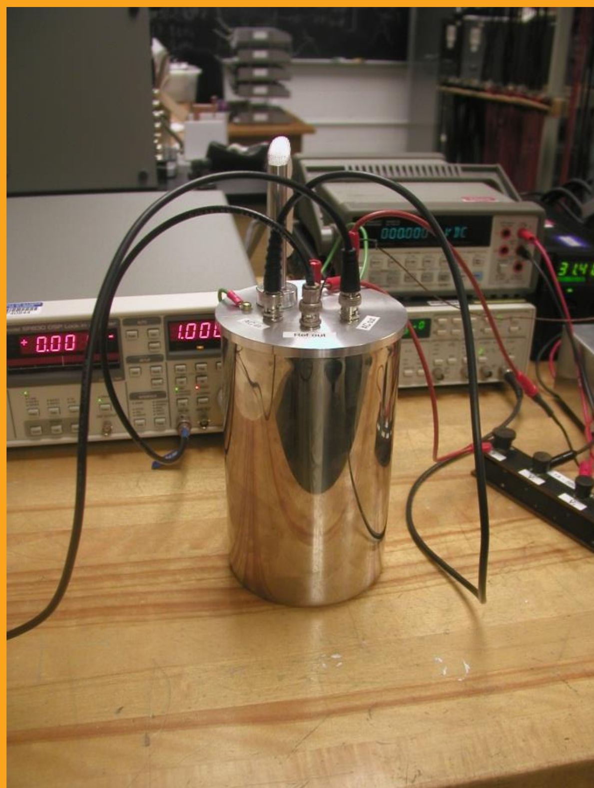
Pierre Ernest Weiss
3.25.1865-10.24.1940



$$\chi' = \frac{C}{T - T_c}$$

Curie-Weiss law

Temperature dependence of the magnetic permeability



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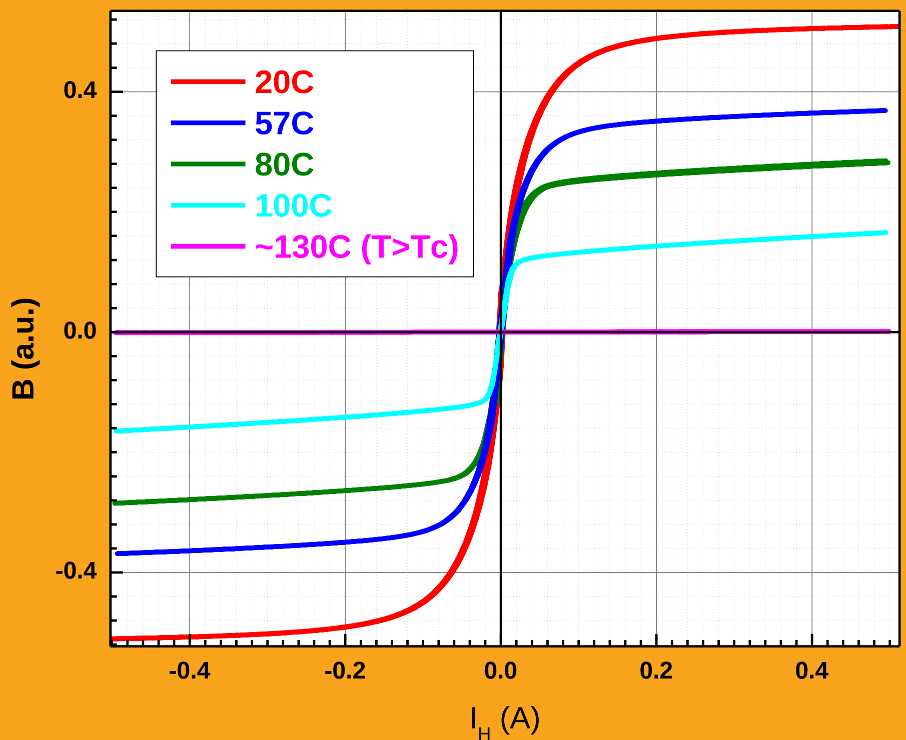

References

- **Information about magnetic materials can be found in : \\Phyaplportal\PHYCS401\Experiments\AC_Magnetization\Magnetic Materials**

- **SR830 manual ibid**

End of semester schedule

- **No Lecture on November 28th**
- **Third week of the Magnetic Laboratory. You can repeat some experiments done during first two weeks + some new challenging experiments like taking B-H dependencies taken at different temperatures or measuring of the permeability as a function frequency with and without DC magnetic field bias.**
- **December 14th Wednesday 11.59pm. Final deadline for submitting of the final report. No extension and no late vouchers.**