Characterization of the 2D percolation transition in ultrathin Fe/W(110) films using the magnetic susceptibility

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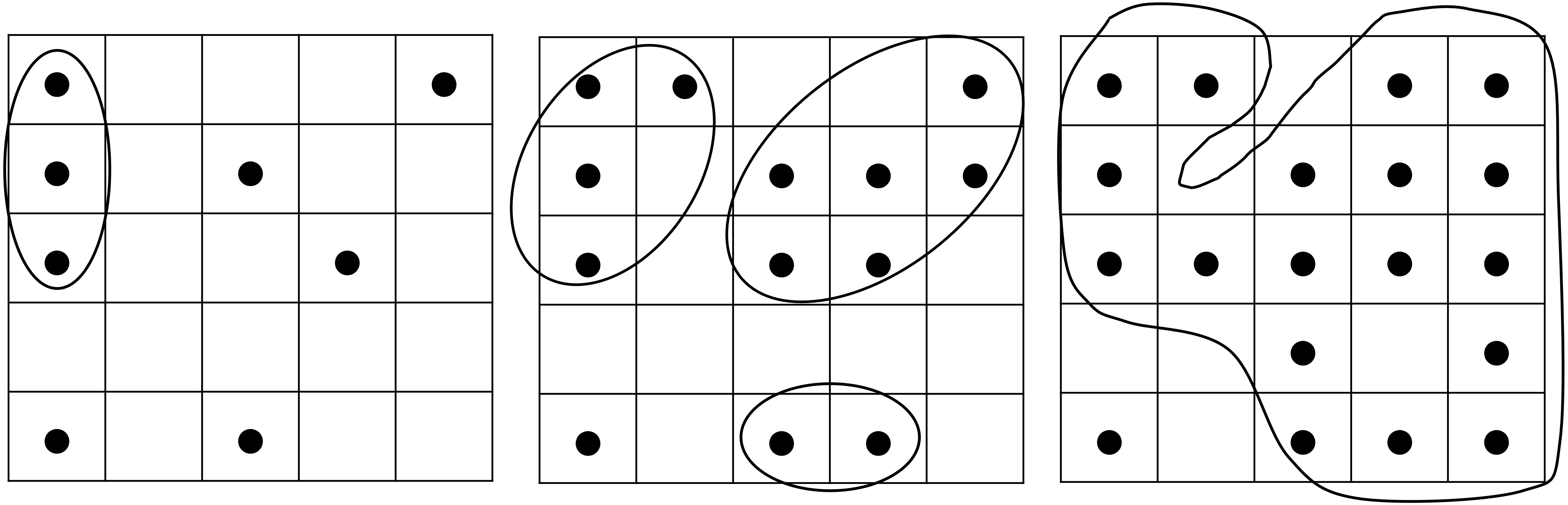
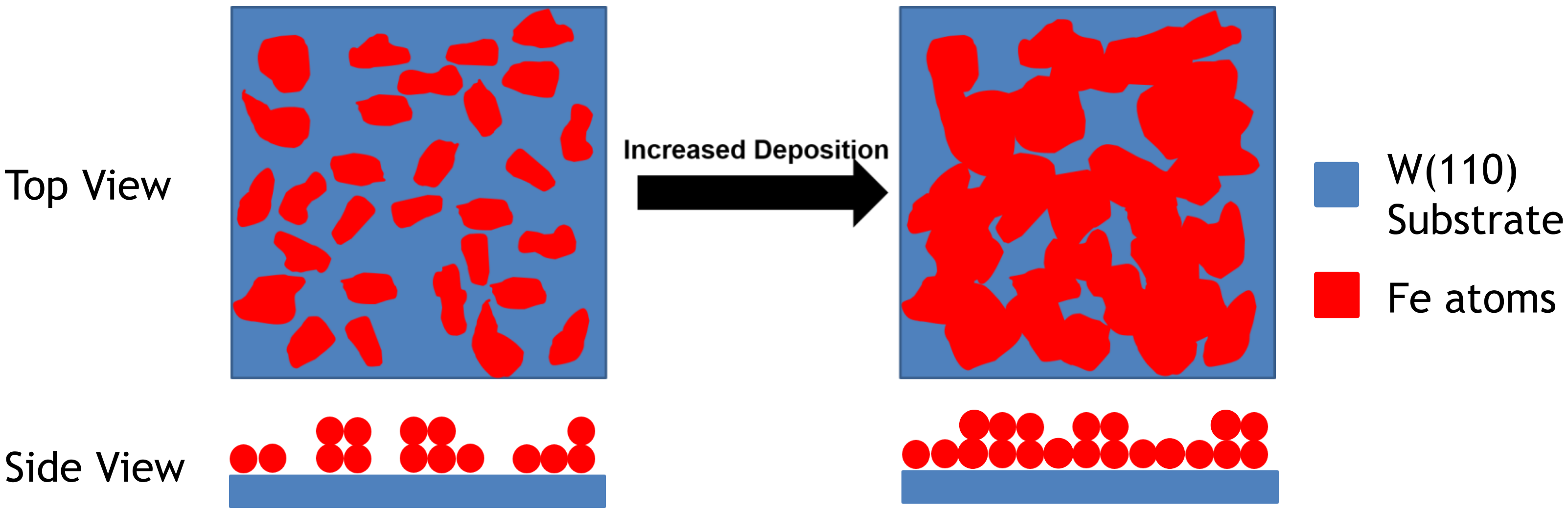
What is Percolation?

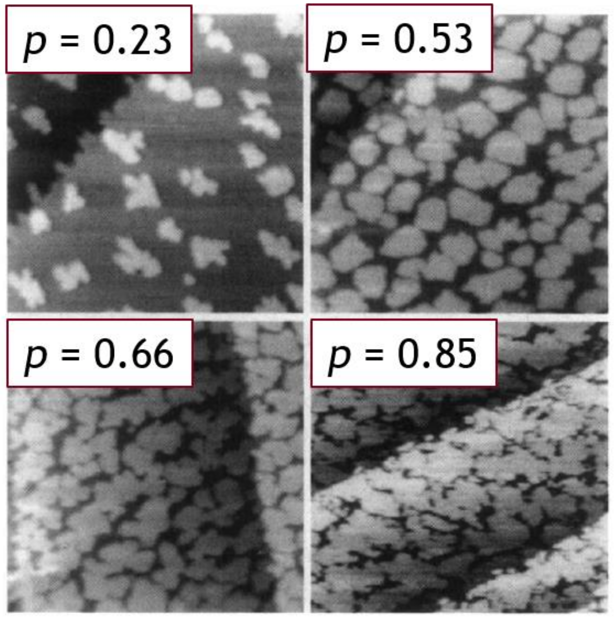


$p = 0.33$ $p = 0.50$ $p = 0.83$

- p_c is the threshold concentration: the point at which a percolating cluster extends the length of the lattice
- $p_c = 0.5928 \ldots$ for an infinite 2D square lattice (theoretical)

Percolation in Ultrathin Films



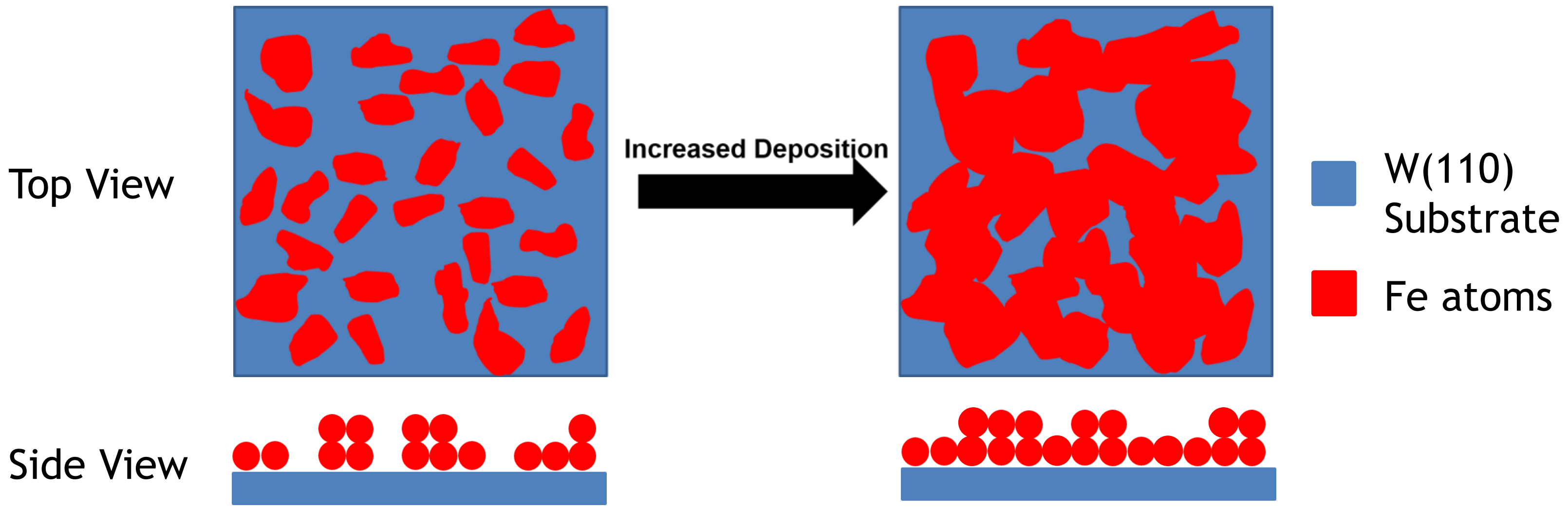


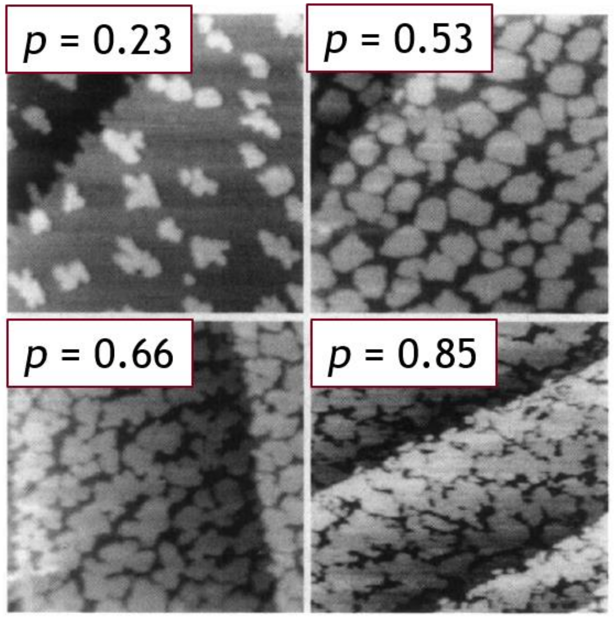
[1]*Elmers, H.J. et al., Phys. Rev. Lett. 73(6), 898-901, (1994).*

Very difficult to study *as the transition is occurring*

Note: Deposition $(t) \neq$ Coverage (p)

Percolation in Ultrathin Films





[1]*Elmers, H.J. et al., Phys. Rev. Lett. 73(6), 898-901, (1994).*

Why is this interesting?

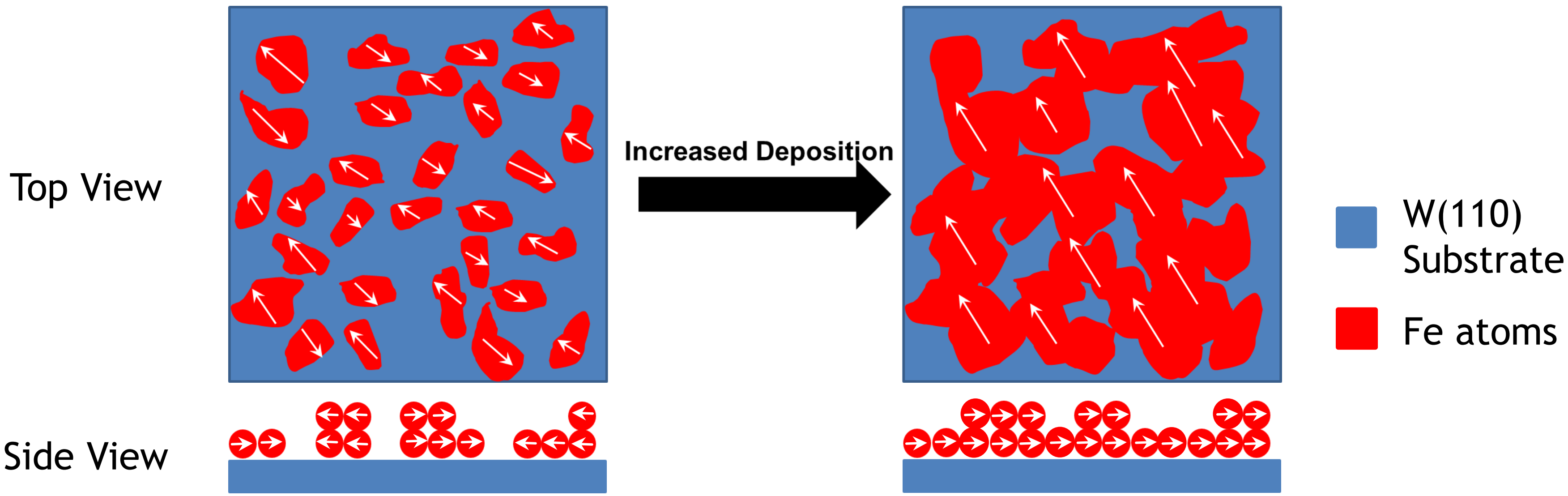
- Radical change in film properties at percolation
- Interesting example of a non-thermal phase transition

Very difficult to study *as the transition is occurring*

Note: Deposition $(t) \neq$ Coverage (p)

Measuring Percolation with Magnetic Susceptibility, χ

$$\chi = \frac{\mathrm{d}M}{\mathrm{d}H}$$



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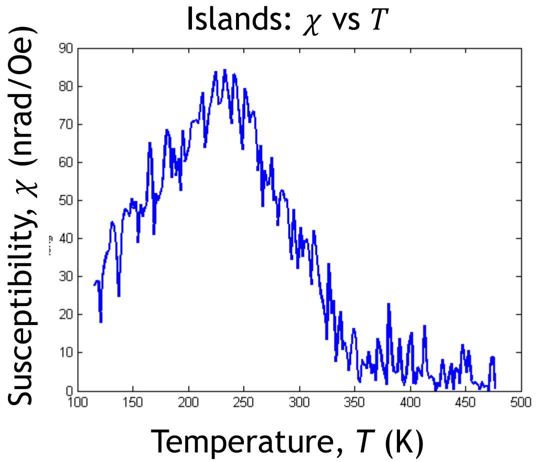

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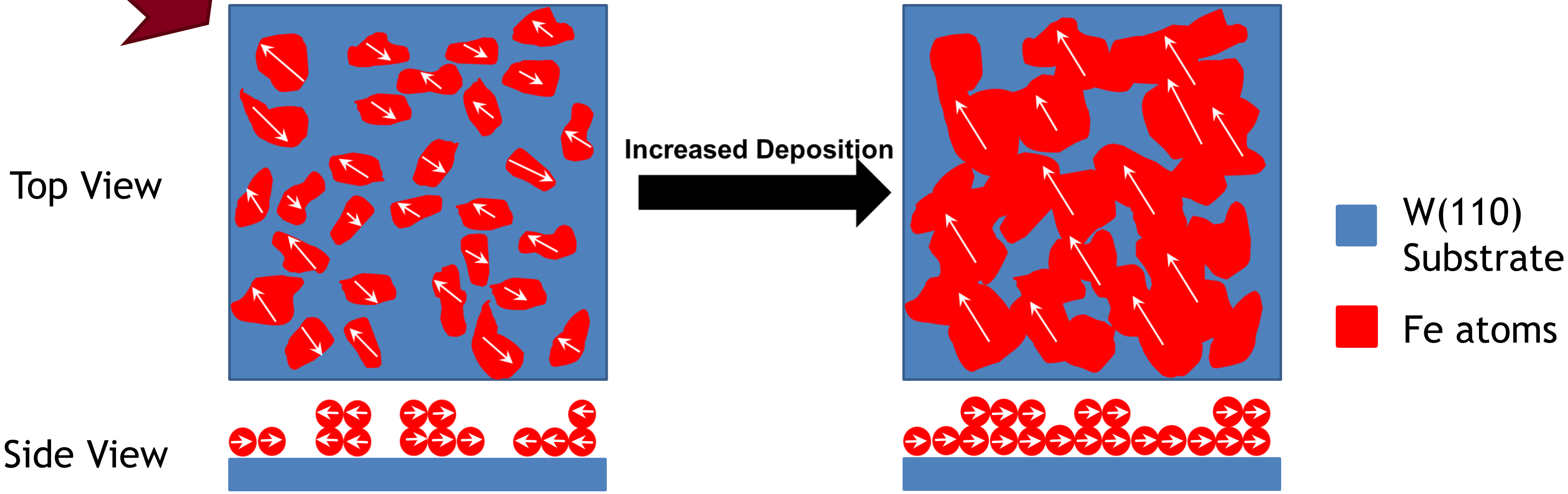

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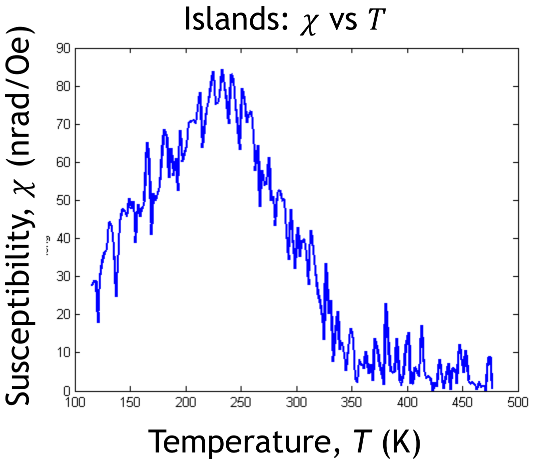

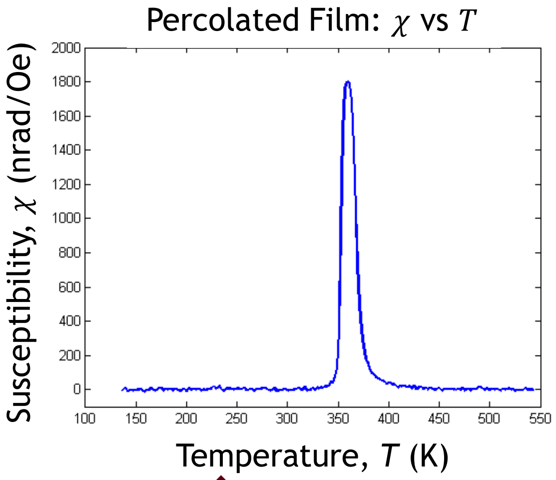

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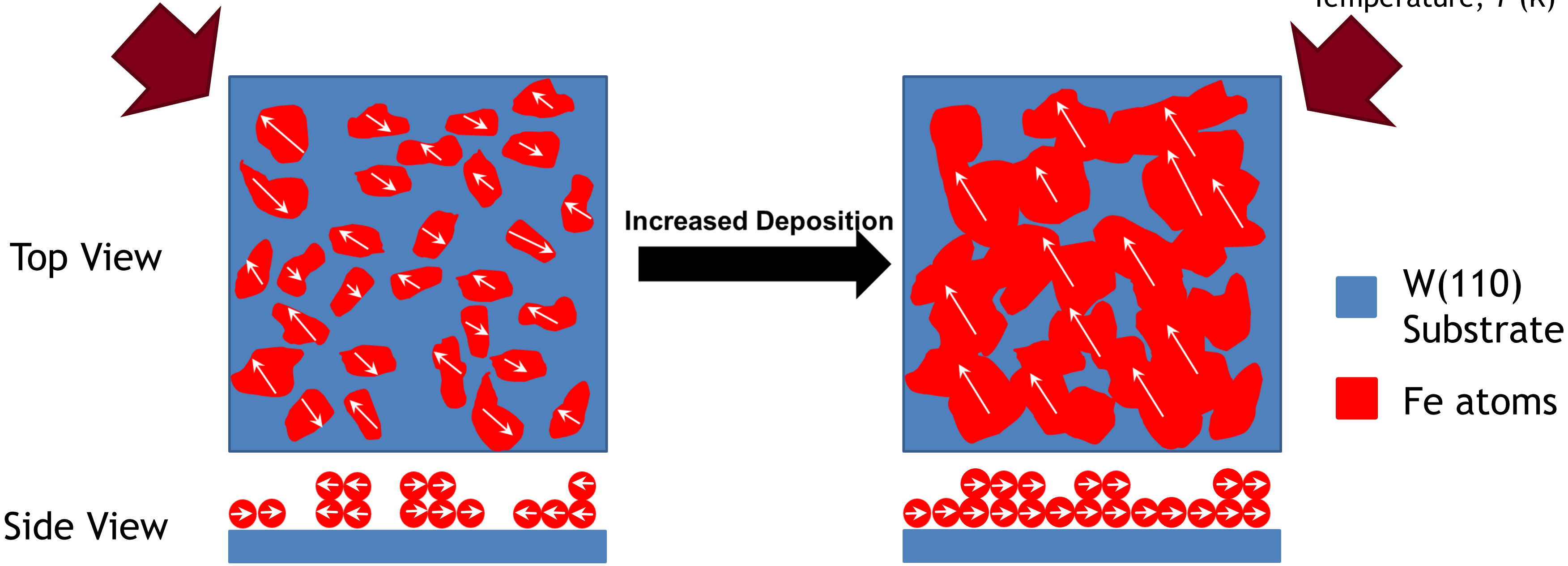
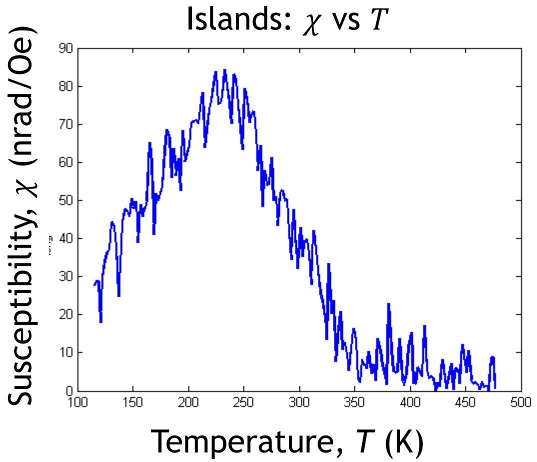
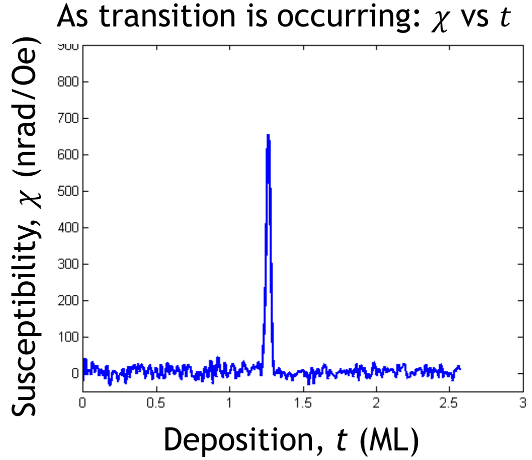
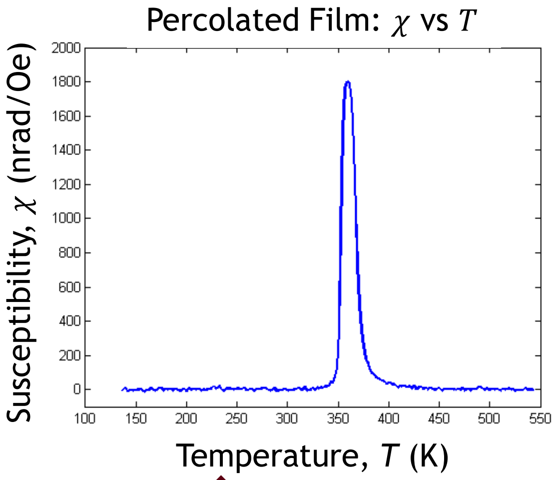


Measuring Percolation with Magnetic Susceptibility, χ



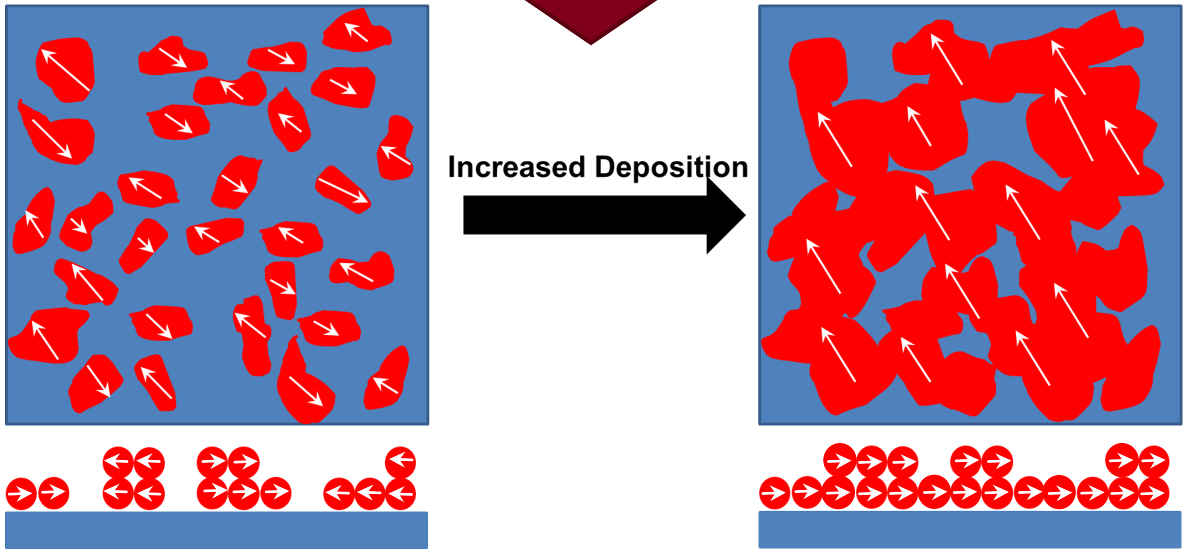




$$\chi = \frac{\mathrm{d}M}{\mathrm{d}H}$$

Top View

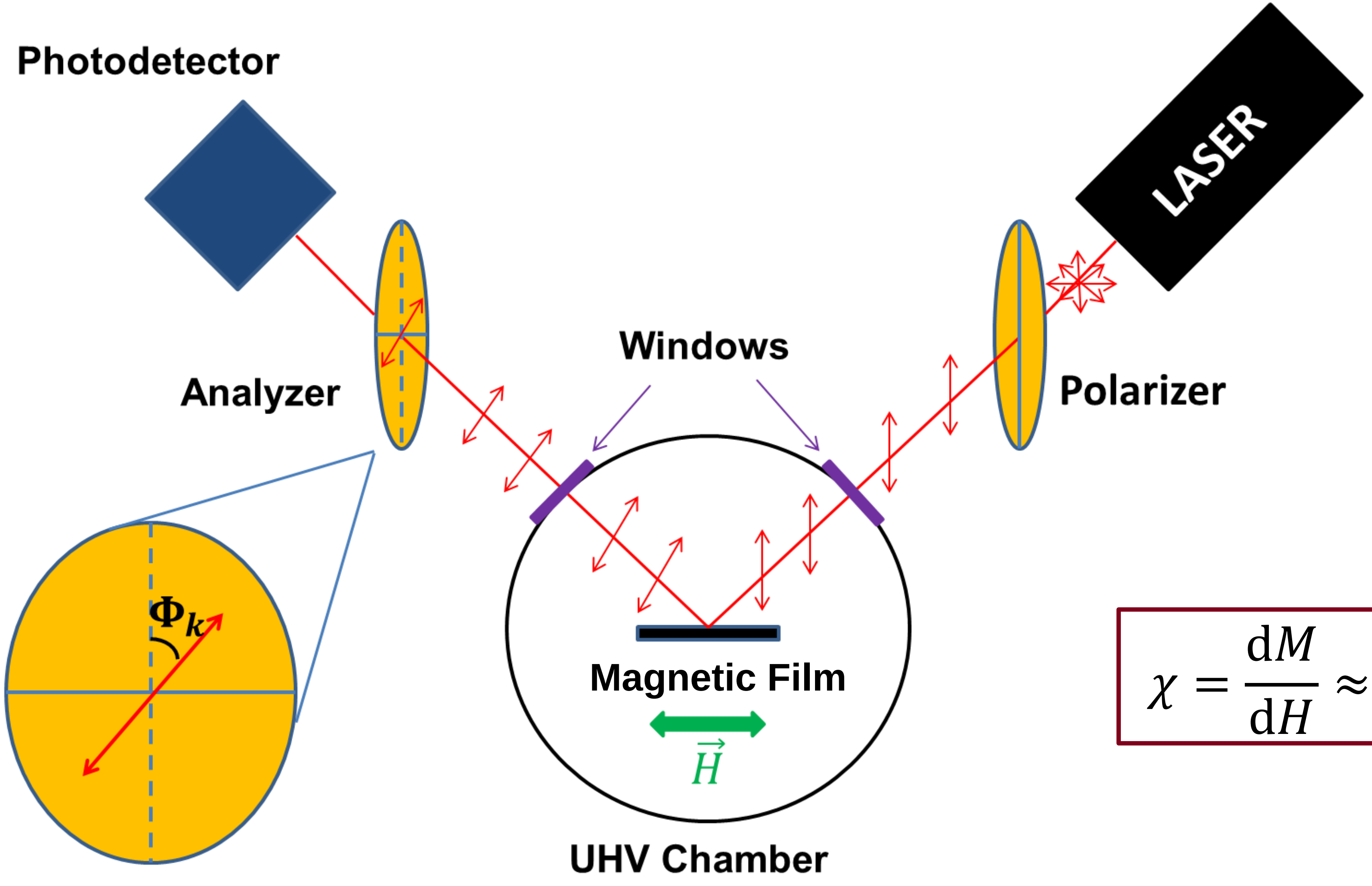
Side View



W(110) Substrate

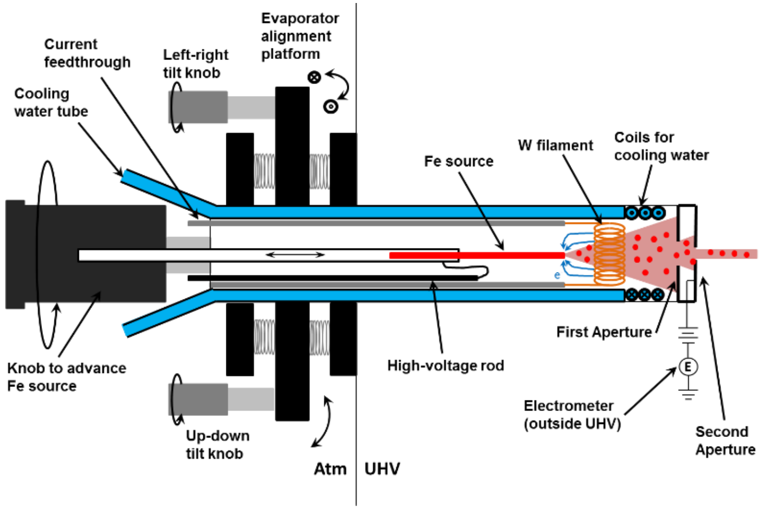
Fe atoms

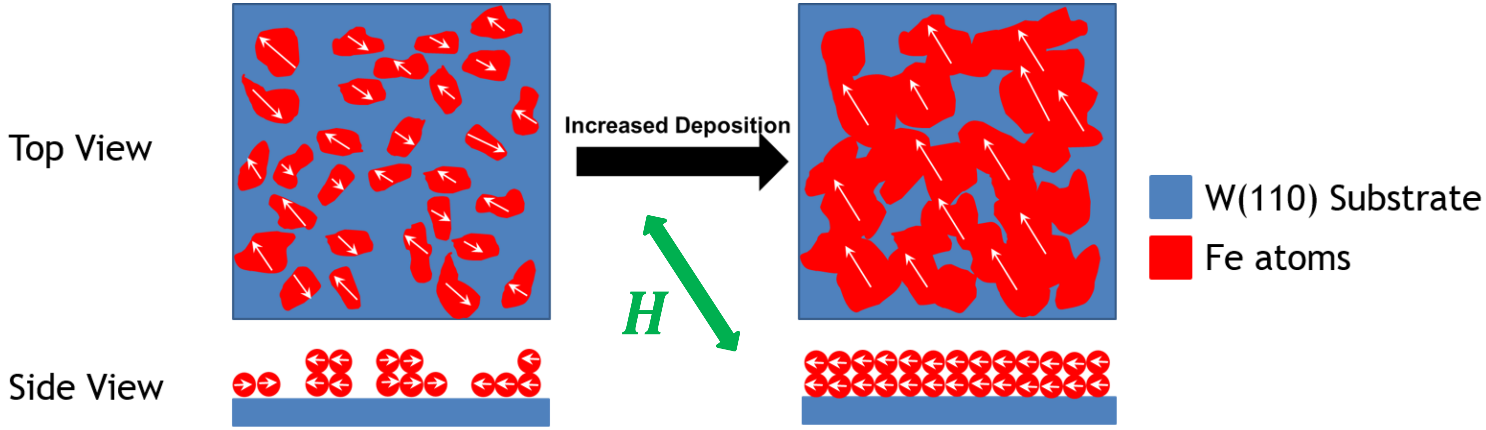
Surface Magneto-optic Kerr Effect



$$\chi = \frac{\mathrm{d}M}{\mathrm{d}H} \approx \frac{\Phi_k}{H}$$

Results: Susceptibility versus deposition





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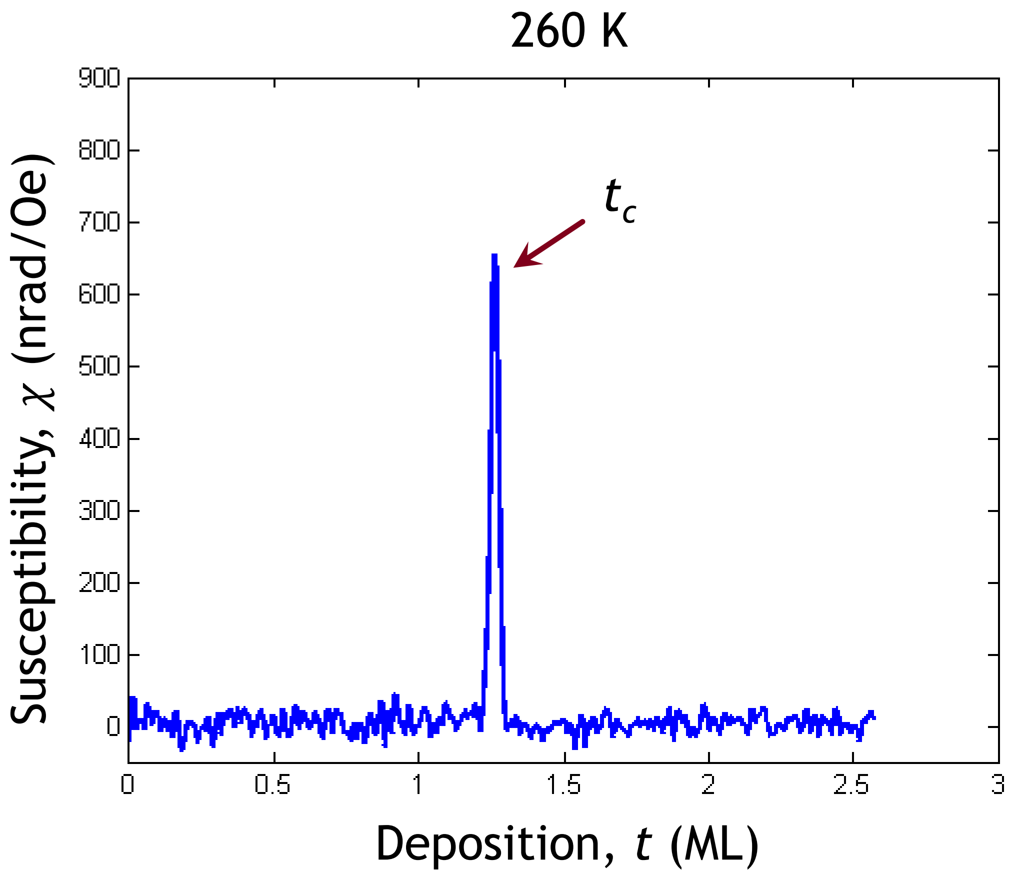

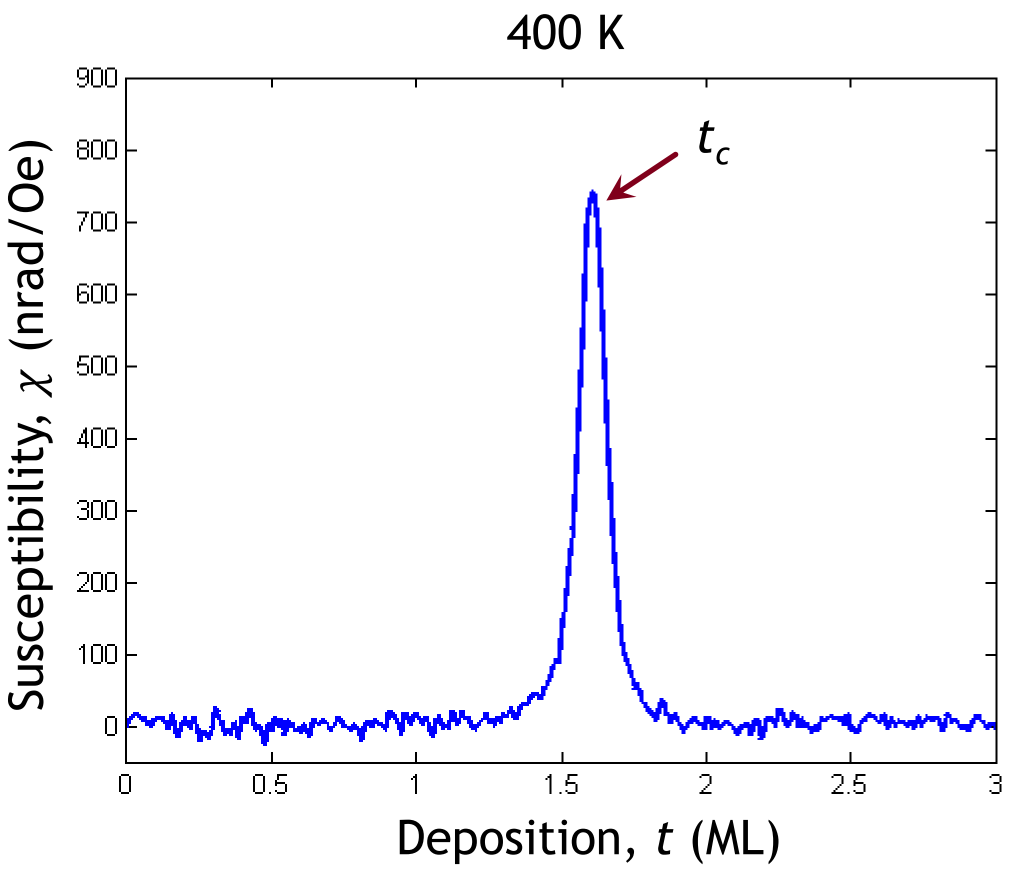

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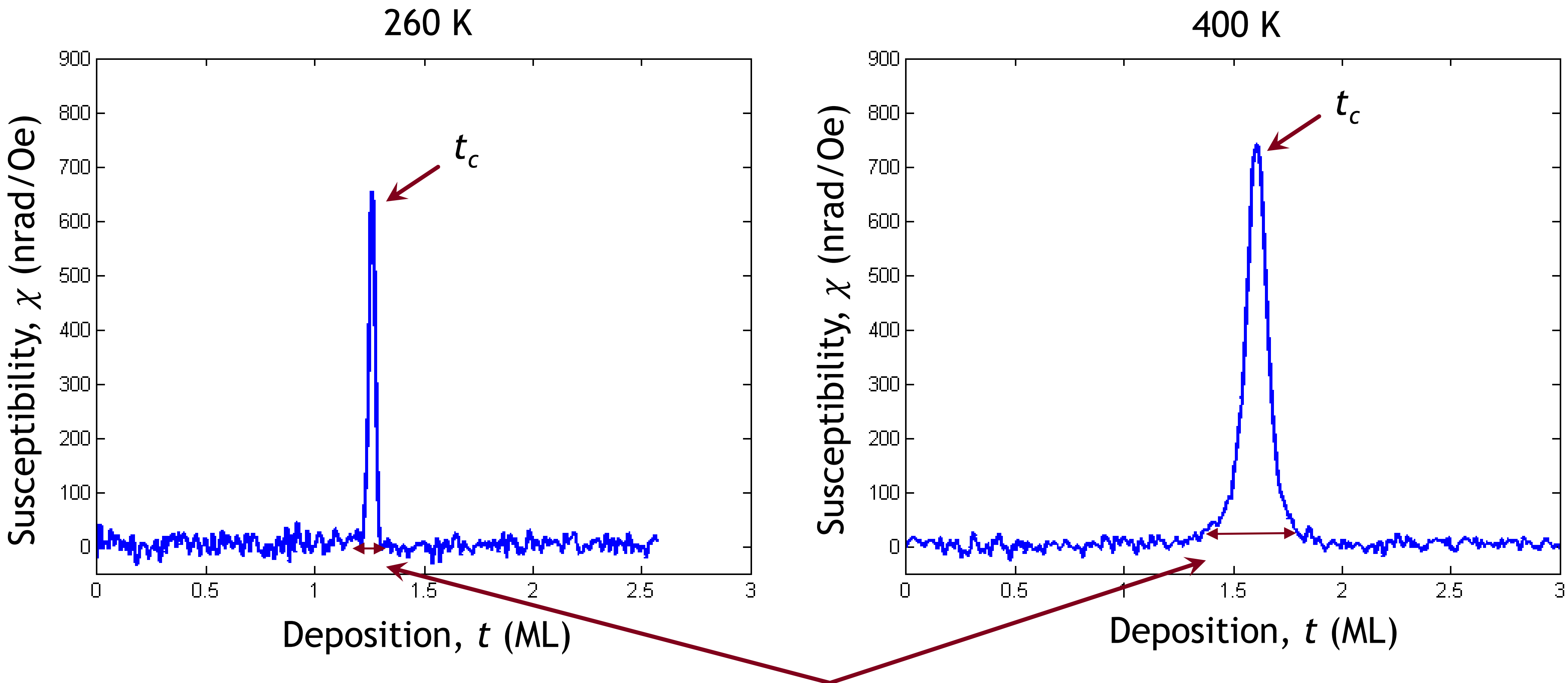
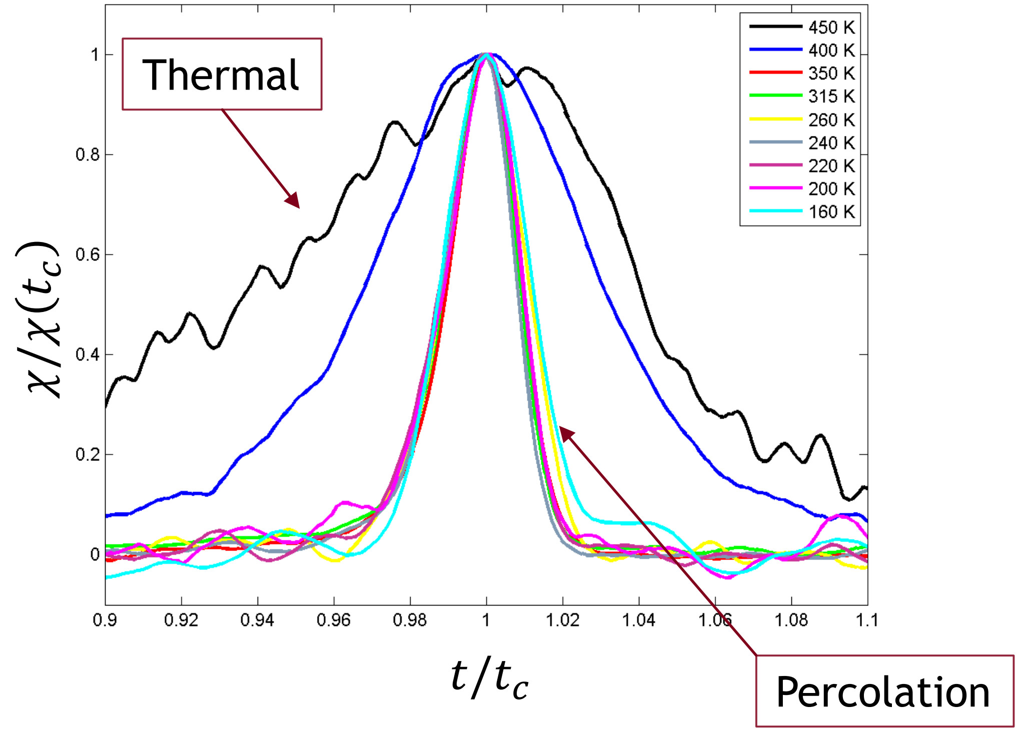


Wider peaks at higher temperature:
suggests different mechanisms

Thermal vs. geometric transitions

- Evidence of different transition types: thermal above ~350 K, percolation below

Scaled shapes of χ at various temperatures



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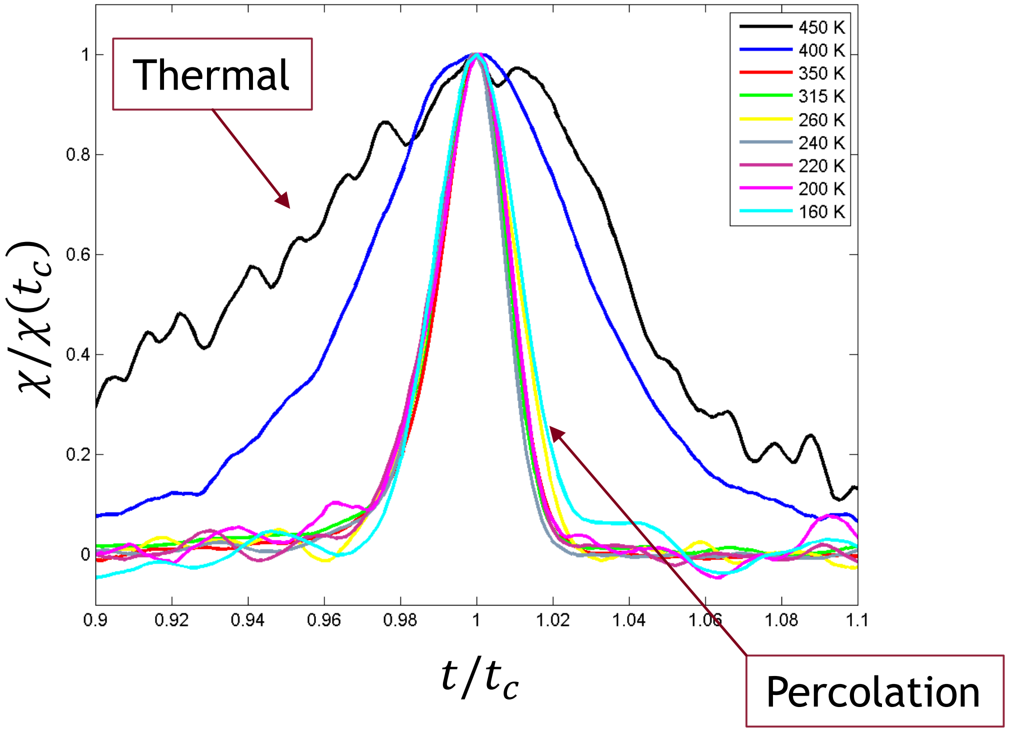
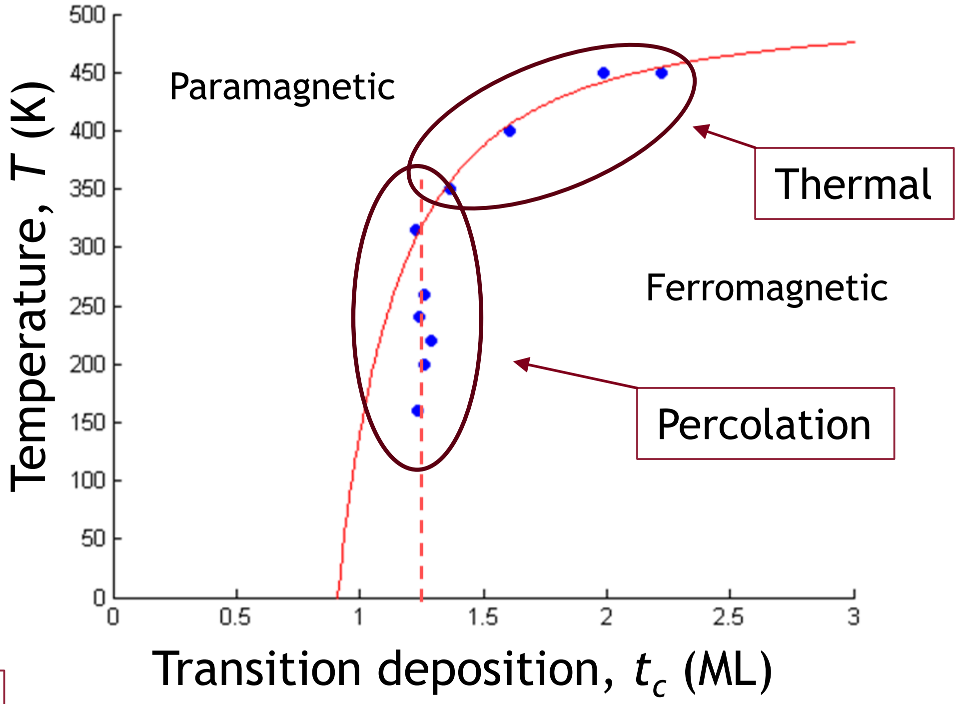
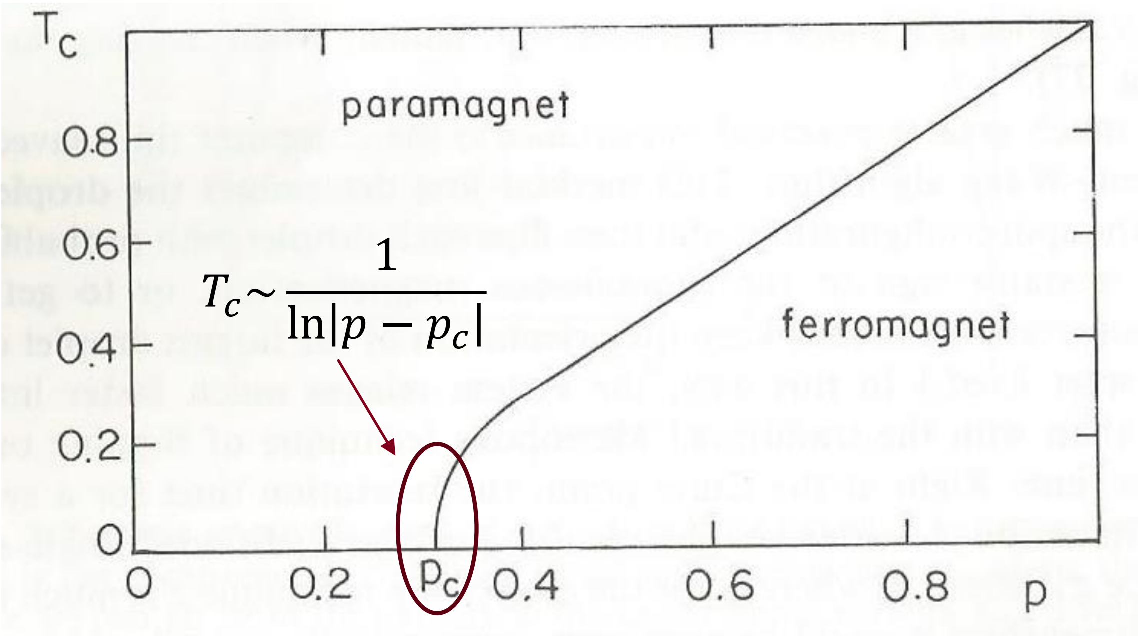


Peak of χ at various temperatures

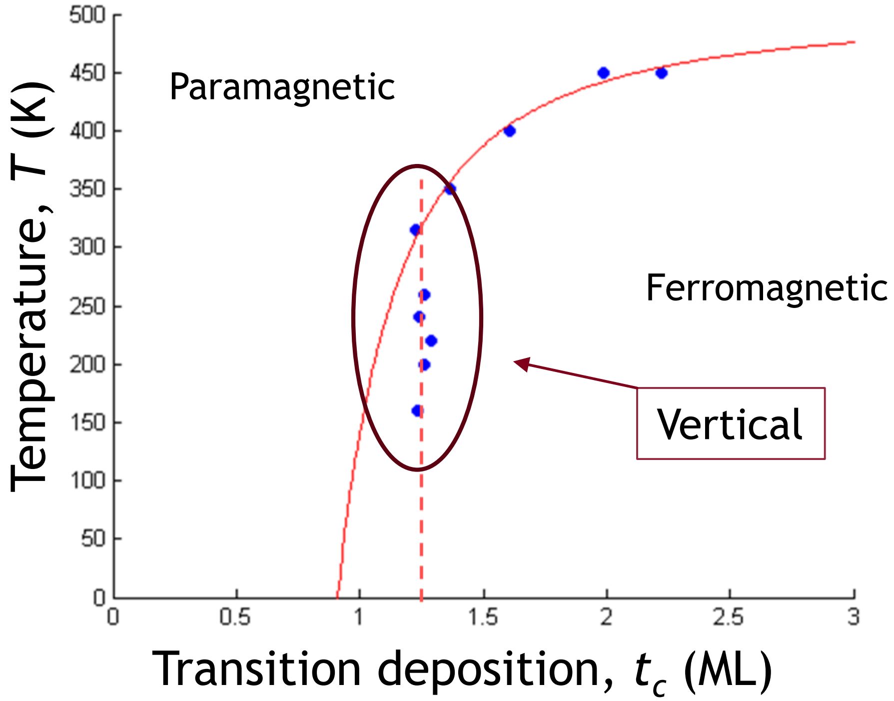


Thermal vs. geometric transitions

- Sharp vertical section agrees qualitatively with theoretically predicted crossover from percolation to thermal behaviour of the transition:



Peak of χ at various temperatures



[1] *Stauer, D. and Aharony, A. Introduction to percolation theory. Taylor & Francis Ltd., (1992).*

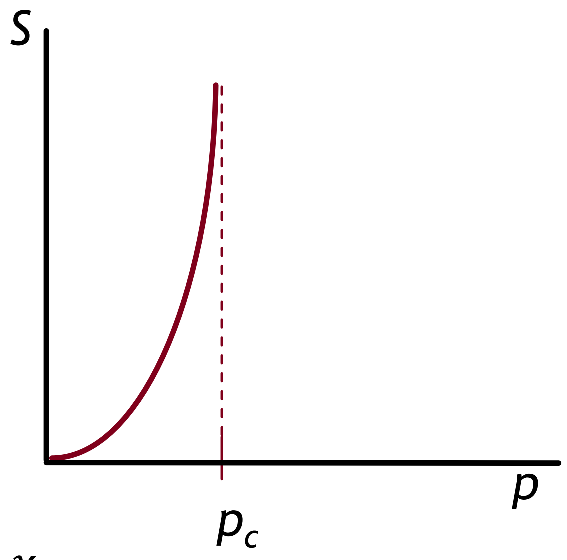
Magnetic susceptibility in terms of percolation

$$M \propto SH$$

Magnetization

Mean Cluster Size

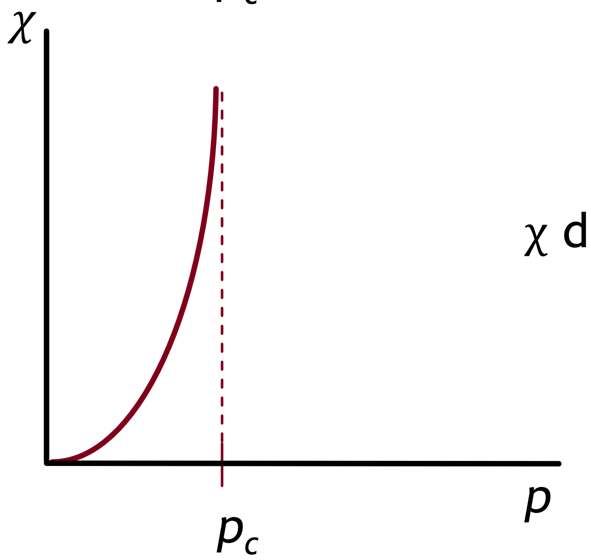
Applied Field



S diverges at p_c

Susceptibility

$$\chi = \frac{\mathrm{d}M}{\mathrm{d}H} \propto S$$



χ diverges as S diverges

Scaling with Critical Exponents

$$\chi \propto |p - p_c|^{-\gamma} \approx |t - t_c|^{-\gamma}$$

Coverage

Percolation Critical Exponent

Deposition

Scaling with Critical Exponents

$$\chi \propto |p - p_c|^{-\gamma} \approx |t - t_c|^{-\gamma}$$

Coverage

Deposition

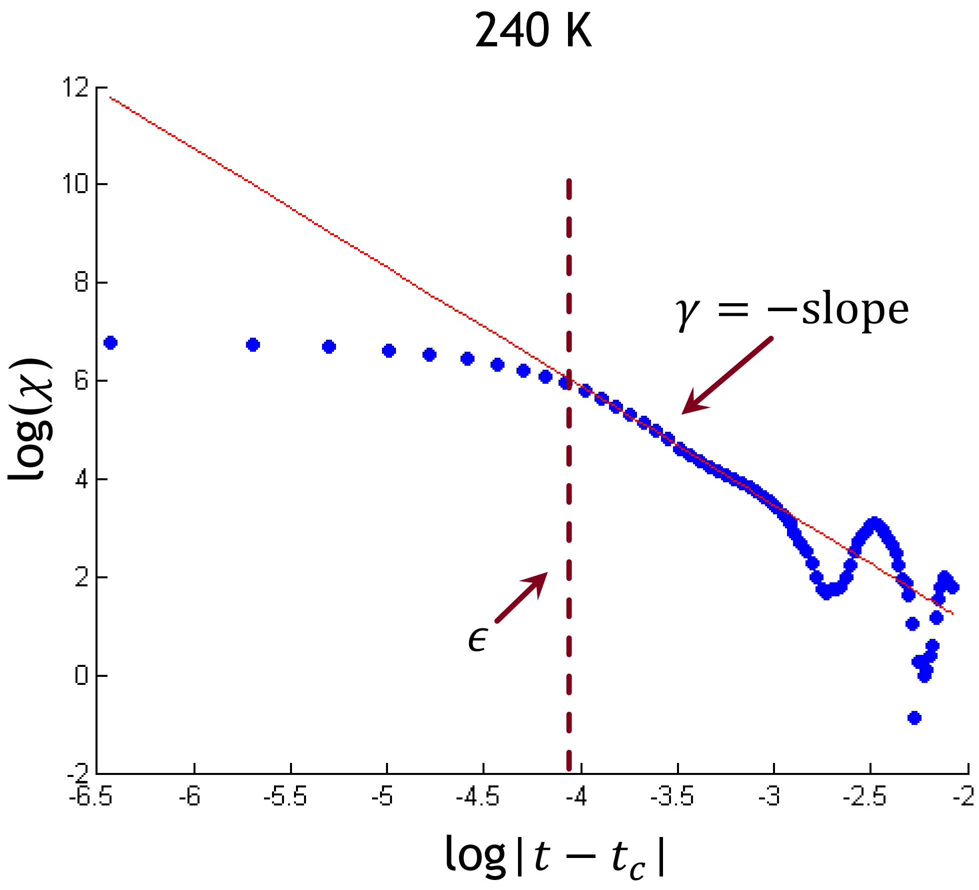
Percolation Critical Exponent

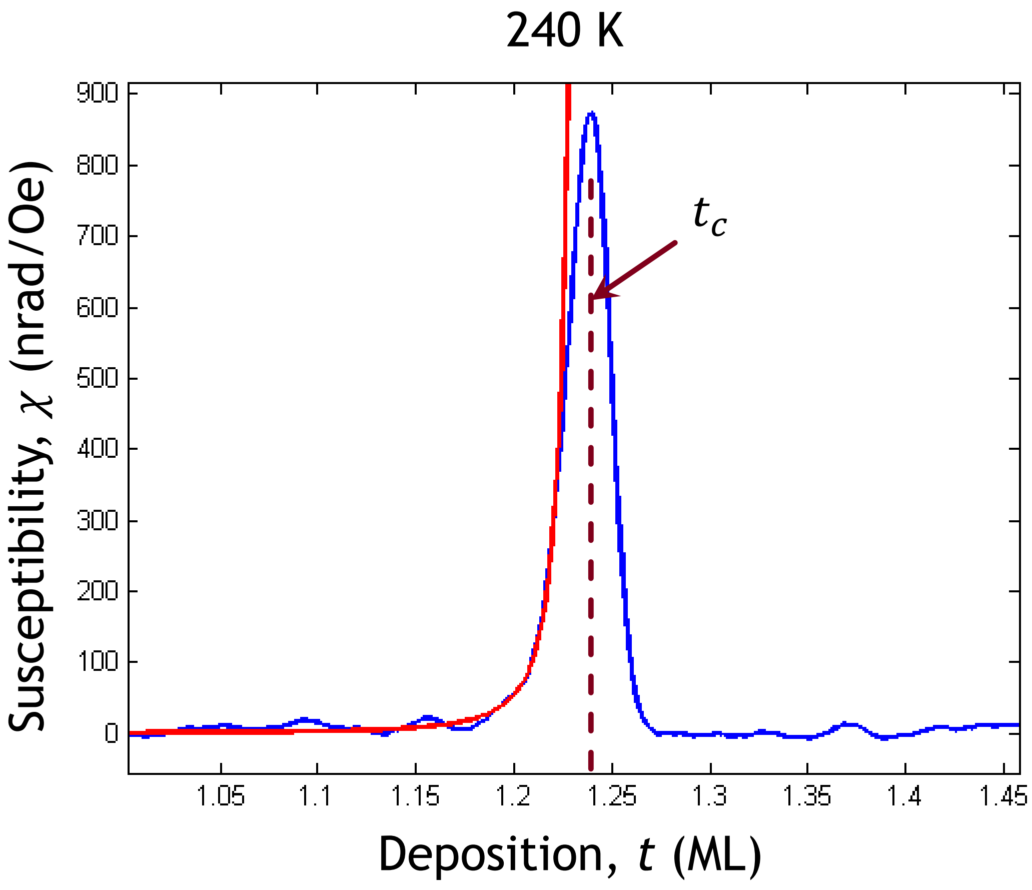
$$\gamma = \frac{43}{18} \approx 2.39$$

From theory (for percolation in 2d)

Fitting to critical exponent

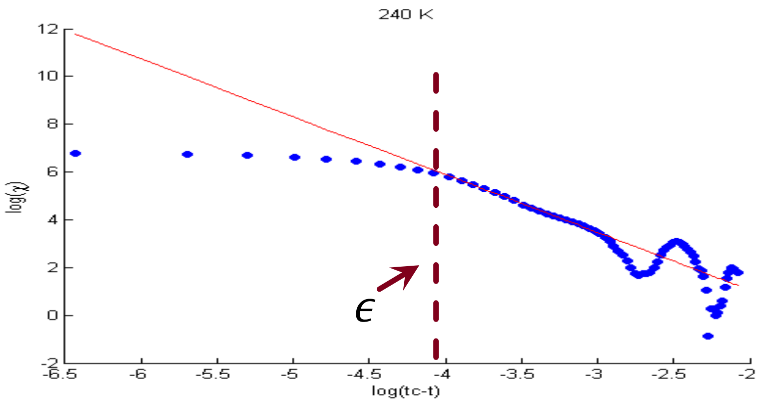
$$\chi = A|t - t_c|^{-\gamma} \quad \Rightarrow \quad \log(\chi) = \log(A) - \gamma \log|t - t_c|$$



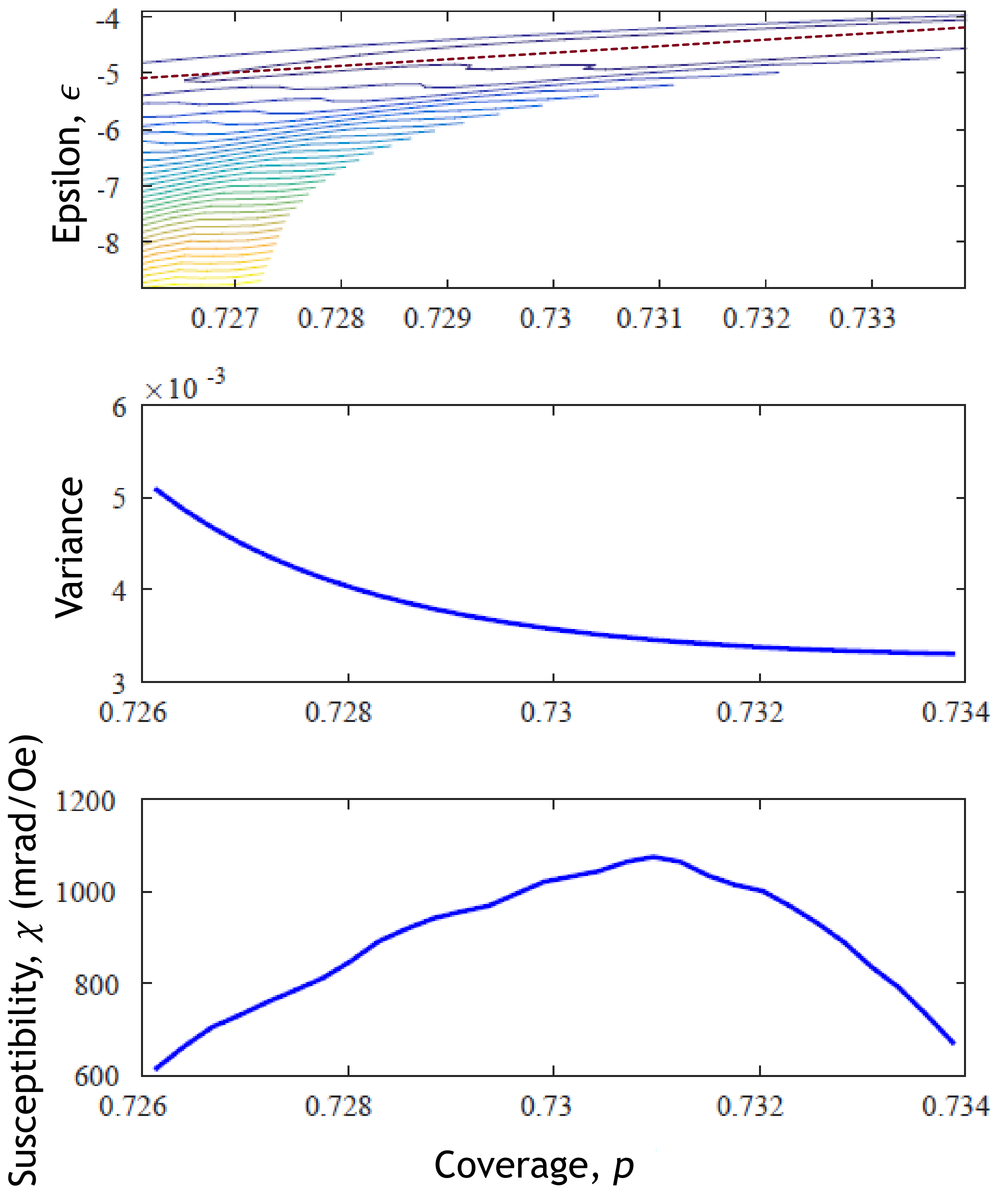


Minimizing variance

- No minimum in the variance
- Variance begins to level out when p_c is chosen close to the peak in the susceptibility



$$\gamma_{mean} = 2.6 \pm 0.2$$



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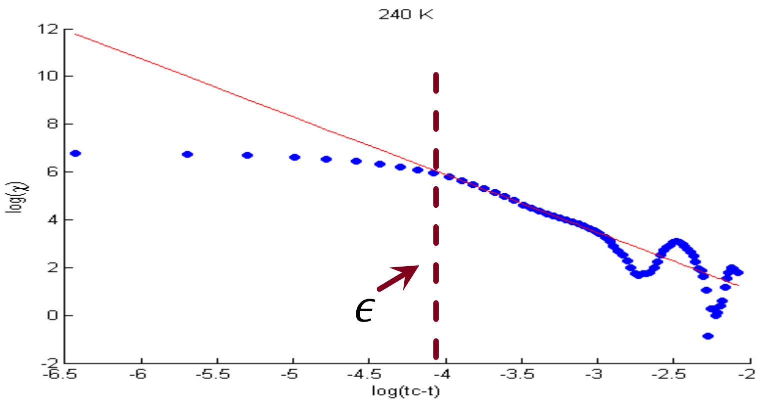
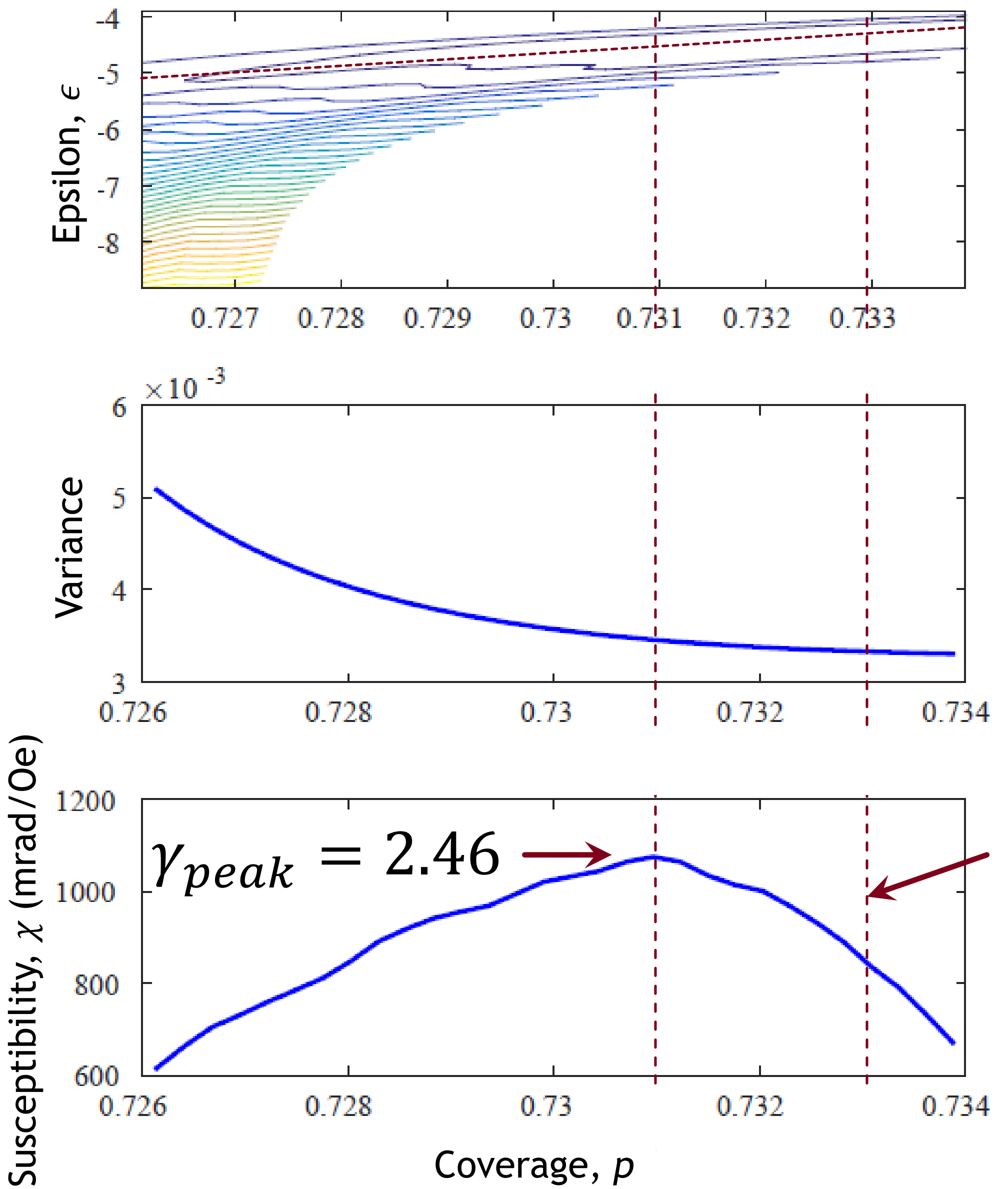




$\gamma_{peak} = 2.46$

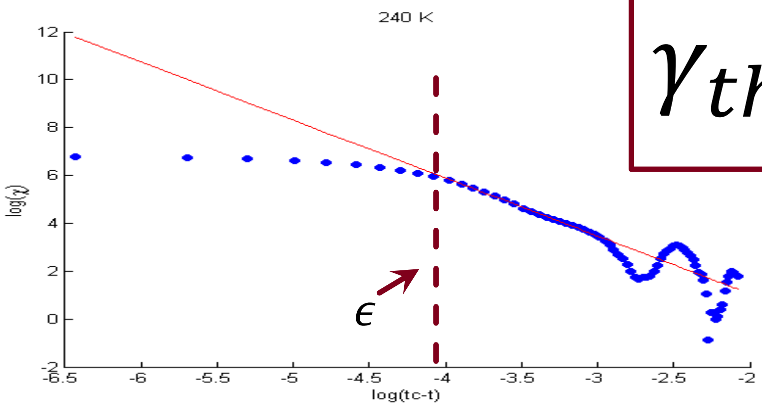
$\gamma_{limit} = 2.82$

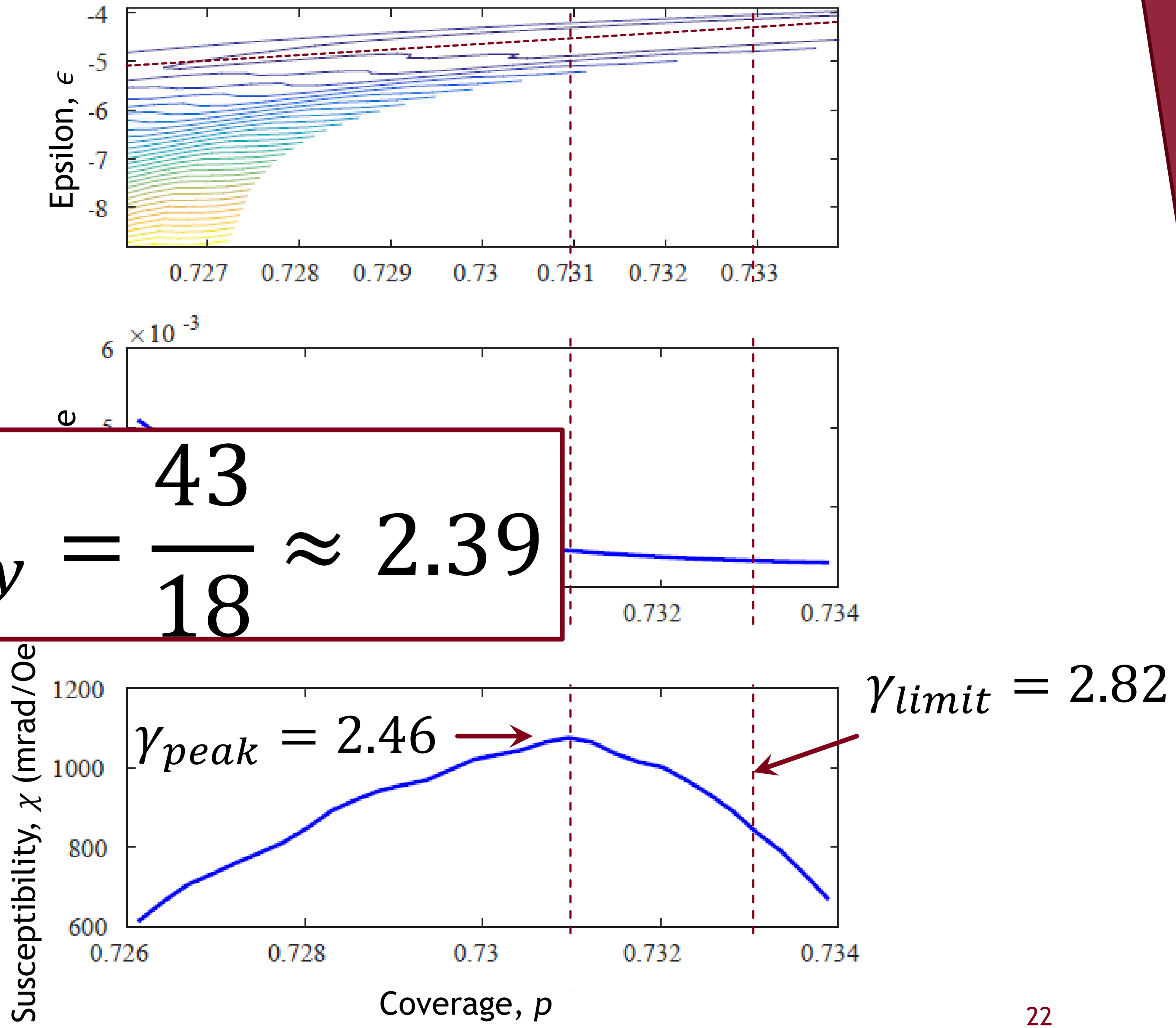
$$\gamma_{mean} = 2.6 \pm 0.2$$

Minimizing variance

- No minimum in the variance
- Variance begins to level out when p_c is chosen close to the peak in the susceptibility

$$\gamma_{theory} = \frac{43}{18} \approx 2.39$$





$$\gamma_{mean} = 2.6 \pm 0.2$$

Conclusions

- Measured and characterized 2D percolation *as it occurs* by using changing magnetic properties as probe

- Observed crossover from percolation to thermal transitions

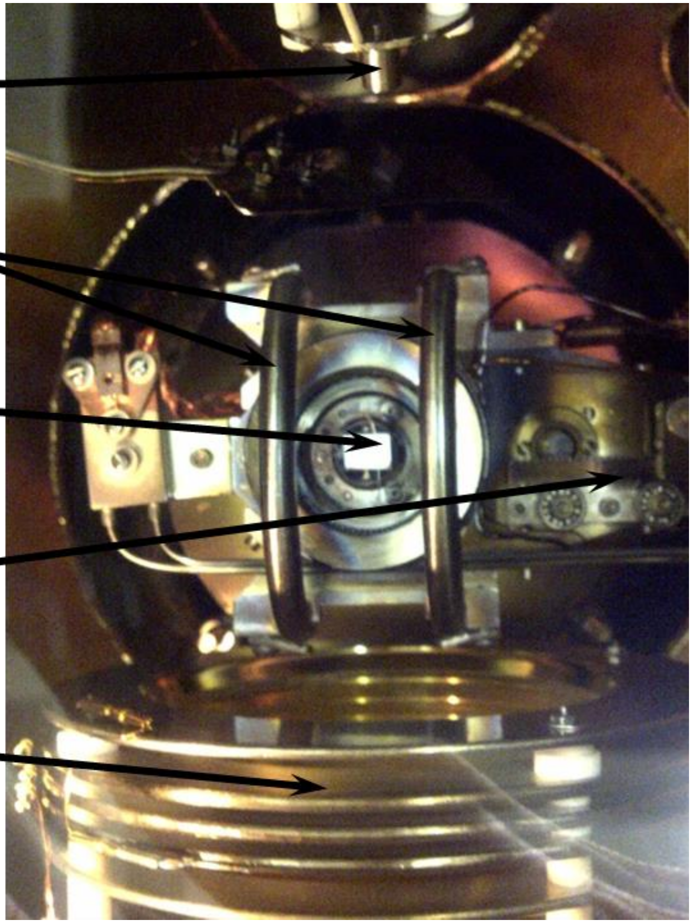
- Agreement with theory
  - Very sharp (essentially vertical) transition line for percolation
  - Critical exponent:
    - Theory: $\gamma = 43/18 \approx 2.39$
    - Experiment: $\gamma = 2.6 \pm 0.2$

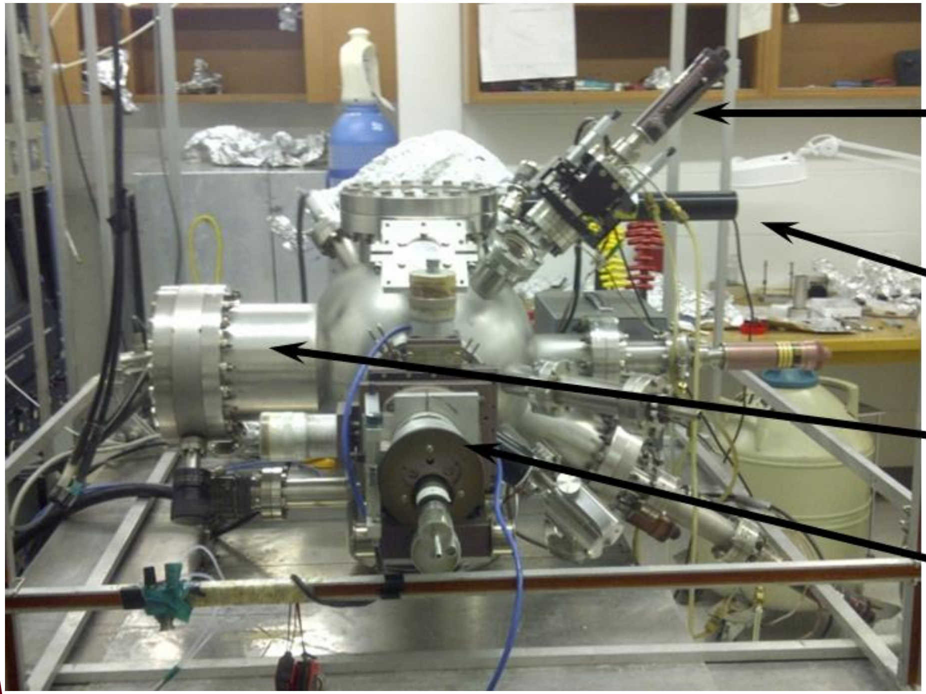
Acknowledgements

- Marek Kiela, Technician
- Gengming He, Former MSc Student

Extra Slides

Apparatus


Fe Evaporator
Helmholtz Coils
W Substrate
Sample Manipulator Arm
AES Apparatus


Fe Evaporator
He-Ne Laser
AES Gun
Sample Manipulator Arm

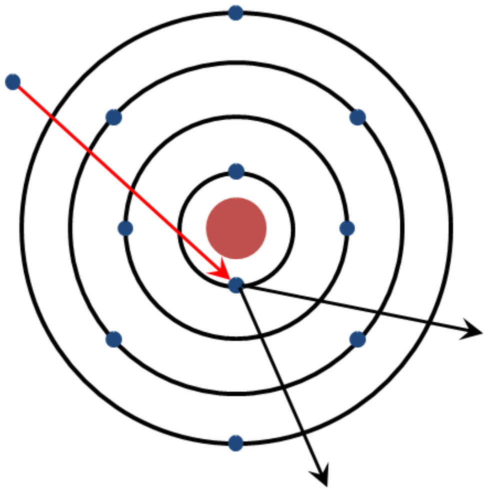
Quartz Window Birefringence

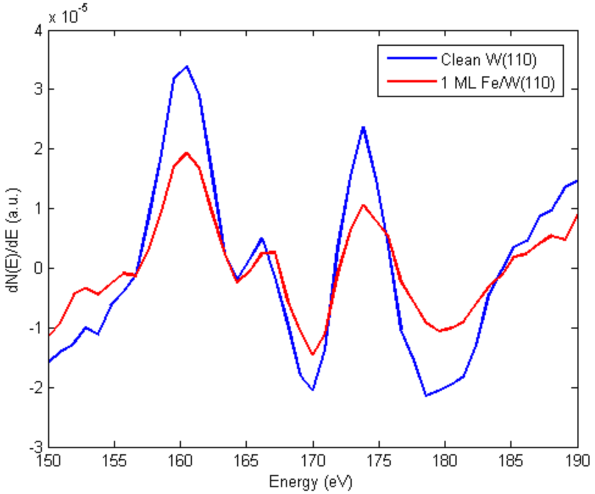
- Strain induced by UHV on quartz windows worsens birefringence
  - Causes linearly polarized light to become elliptically polarized upon entering the chamber.
- Method developed to counteract effect[1]
  - Initial polarizer rotated slightly such that ellipticity from sample counteracts ellipticity from windows resulting in linearly polarized light at analyzer

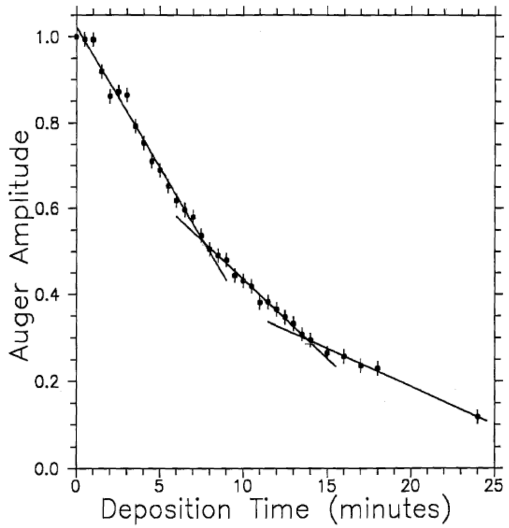
[1]*Arnold, C.S. and Venus, D., Rev. Sci. Instrum. 68(11), 4212-4216 (1997).*
Include references

Measuring Film Thickness

- Film thickness measured by Auger Electron Spectroscopy (AES)
- Measure W spectrum before and after film growth: attenuation proportional to the deposition up to the first ML



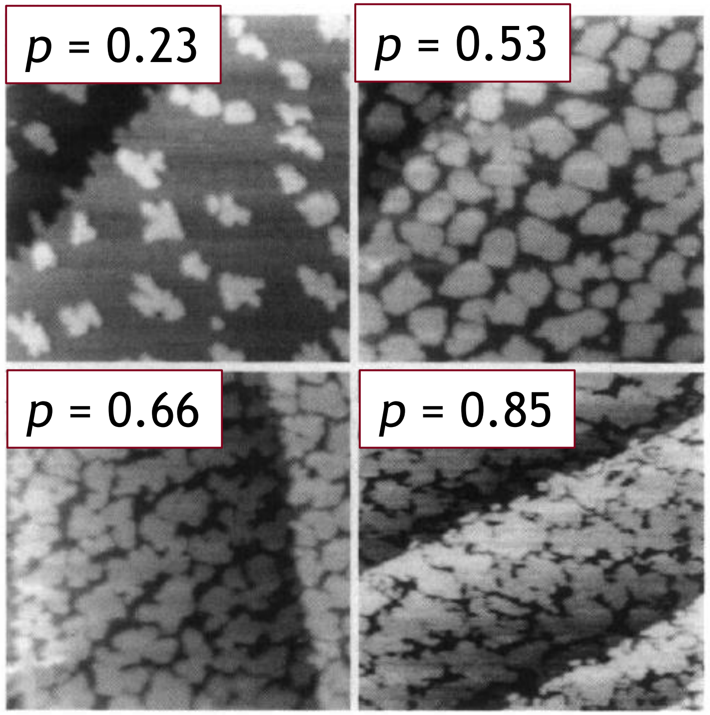




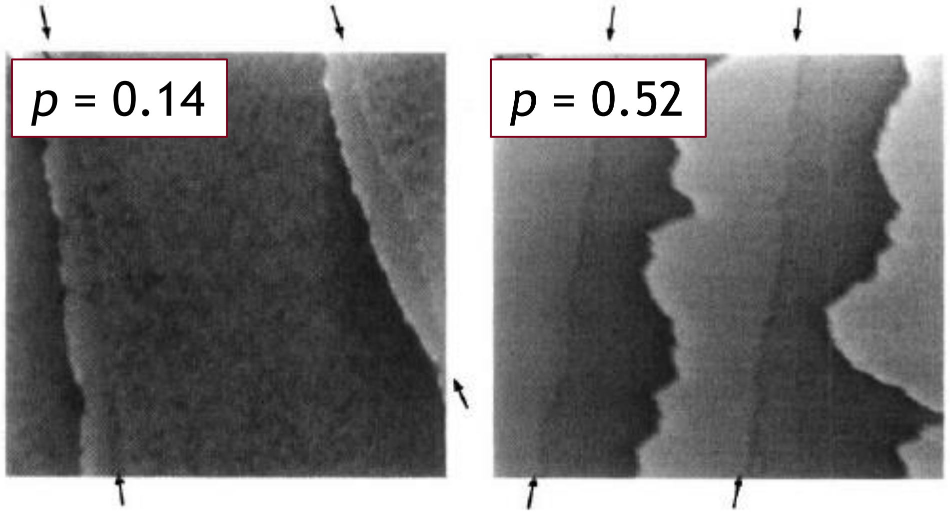
[1]Jones, T. Master's thesis, McMaster University, Hamilton, Ontario, (1997).

Growth Modes

- At room temperature, growth by isolated islands (quenched magnet)



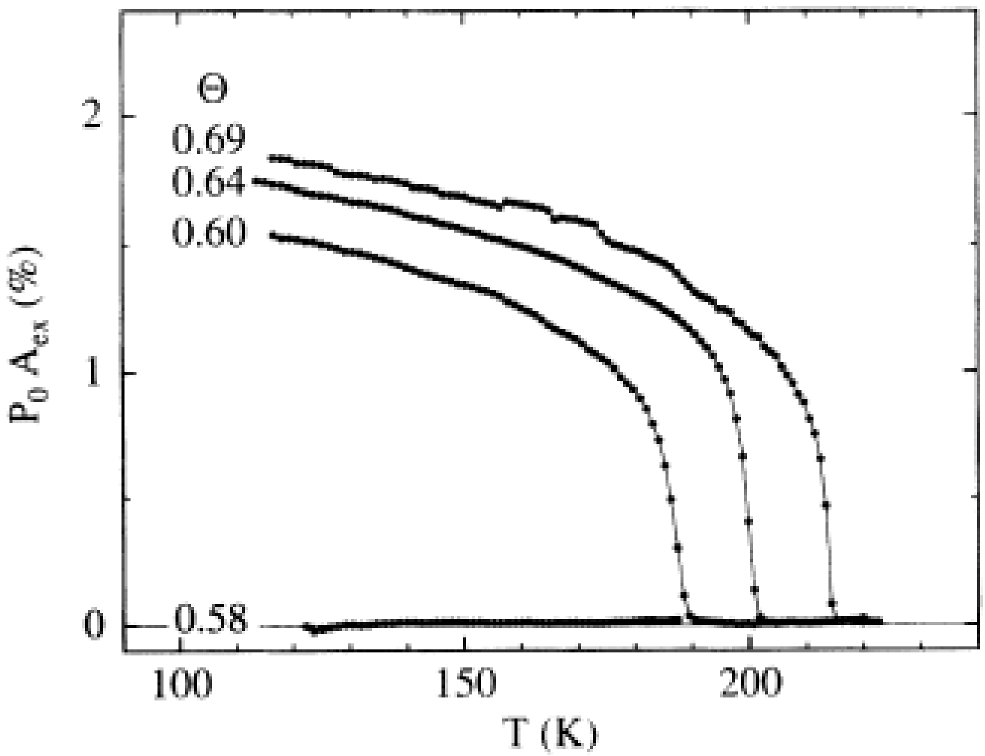
- At >500K, growth by stripes (annealed magnet)
  - Grows along terrace step edges
    - terraces due to cleaving of mosaic W crystal to reveal (110) surface.
  - Growth is monolayer by monolayer



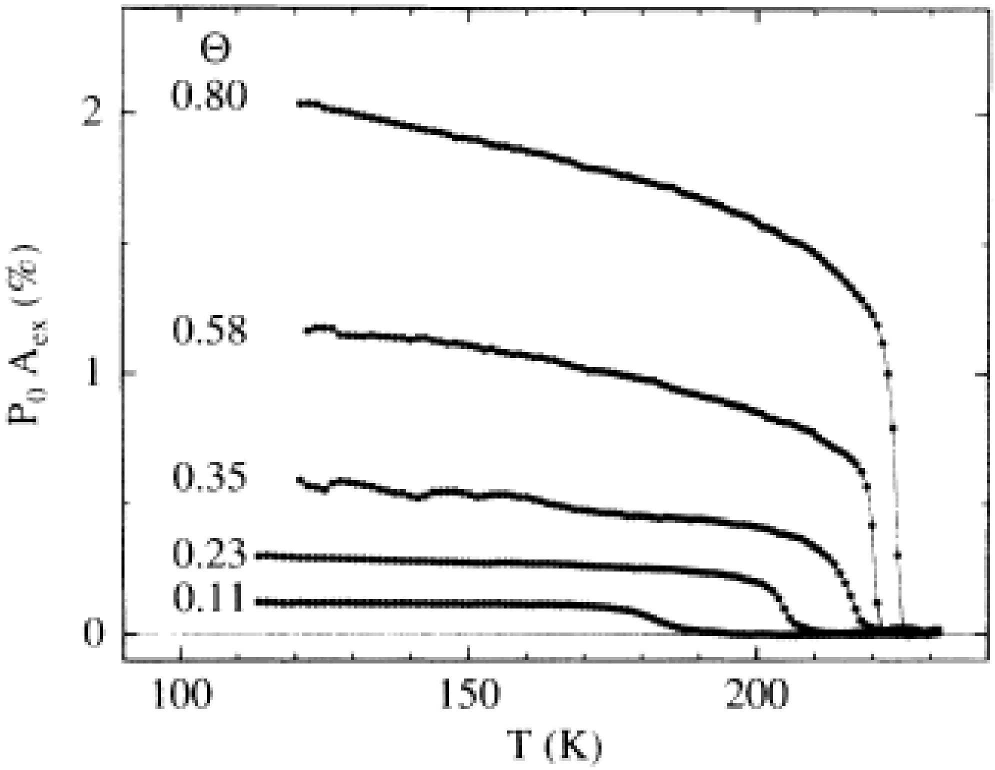
Elmers, H.J. et al., Phys. Rev. Lett. 73(6), 898-901, (1994).

Indirect Observation of Percolation

Growth at Room Temp

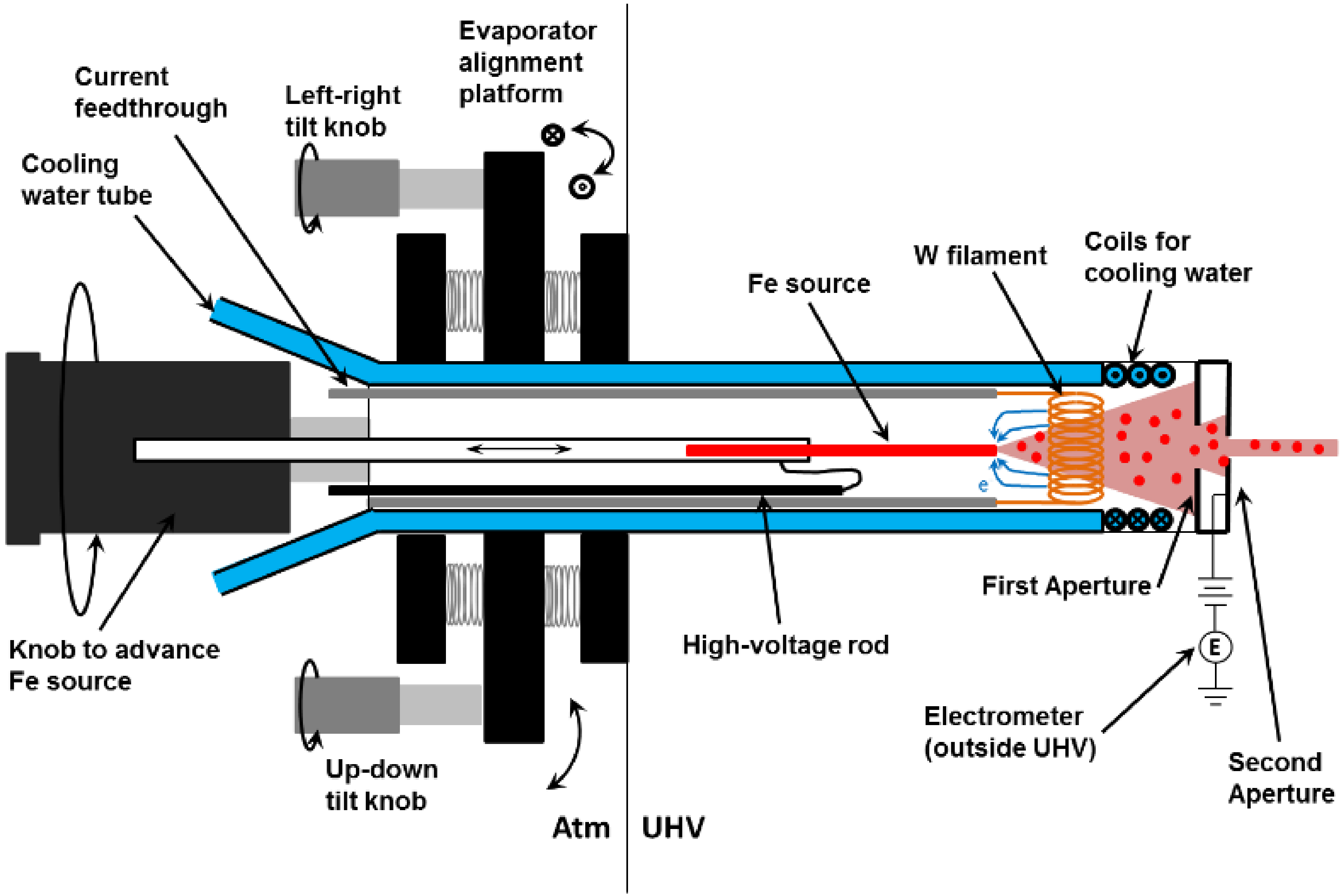


Growth at 660K



Elmers, H.J. et al., Phys. Rev. Lett. 73(6), 898-901, (1994).

Evaporator



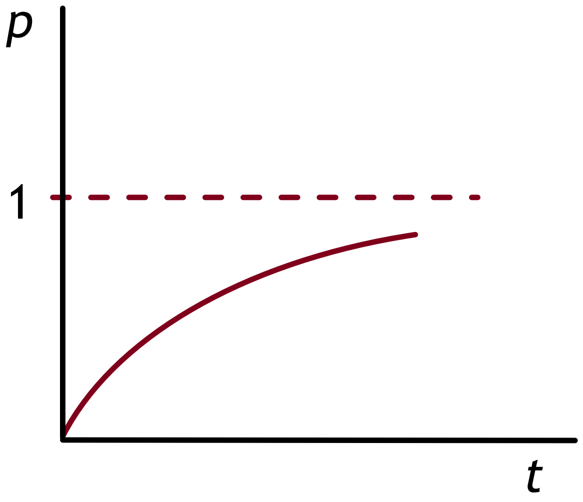
Evaporator alignment platform
Current feedthrough
Left-right tilt knob
Cooling water tube
W filament
Coils for cooling water
Fe source
e
Knob to advance Fe source
High-voltage rod
First Aperture
E
Electrometer (outside UHV)
Second Aperture
Up-down tilt knob
Atm
UHV

Relation between coverage, *p*, and deposition, *t*

- A simple model of particles landing randomly on lattice sites
- Particles are permitted to land on other particles
- Particles more likely to land on other particles at higher coverages p

$$p = 1 - e^{-t}$$

For critical deposition, $t_c = 1.2\text{ML} \Rightarrow p \approx 0.7$



Derivation of Susceptibility for Percolation

Magnetization of a single cluster: $m_{cluster} = sm\tanh\left(\frac{smH}{kT}\right)$

Film magnetization: $M = \sum_s m_{cluster} n_s = \sum_s smn_s \tanh\left(\frac{smH}{kT}\right) \approx \sum_s \frac{(sm)^2 n_s H}{kT}$

Mean cluster size: $S = \frac{\sum_s s^2 n_s}{\sum_s sn_s}$

Susceptibility: $\chi = \frac{\mathrm{d}M}{\mathrm{d}H} = \frac{m^2}{kT} \sum_S s^2 n_s \Rightarrow \chi \propto S$

s = number of lattice sites in a cluster
m = magnetic moment of single atom
H = applied field
n_s = number of clusters of size *s* per lattice site