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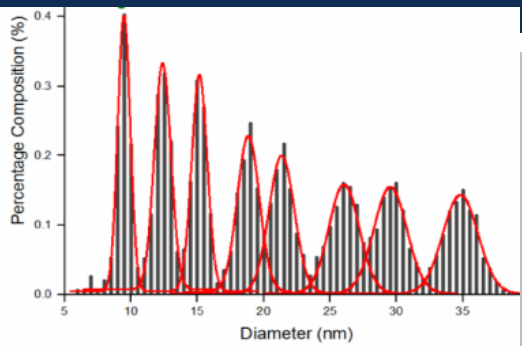

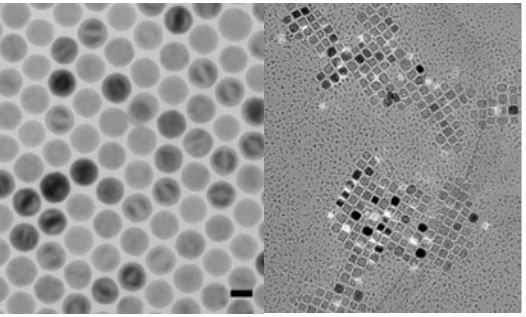

Magnetic Nancomposite for Inductor Applications

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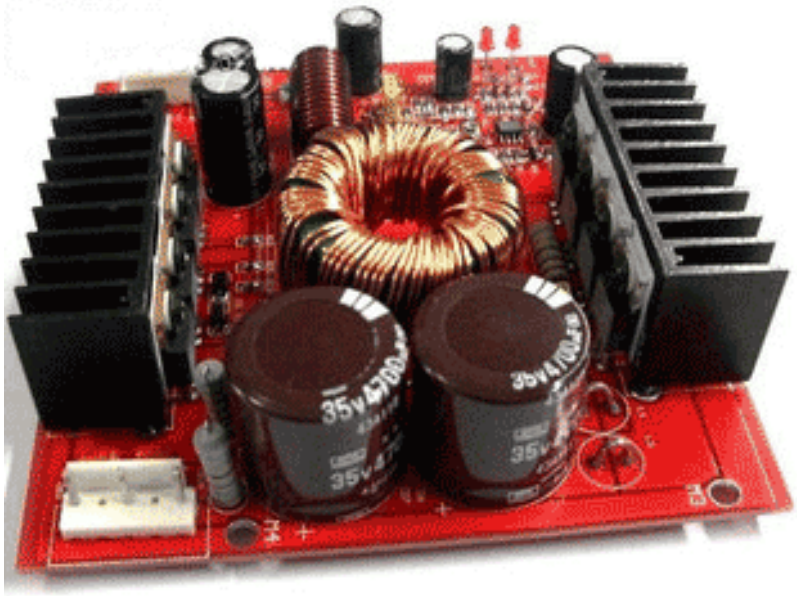
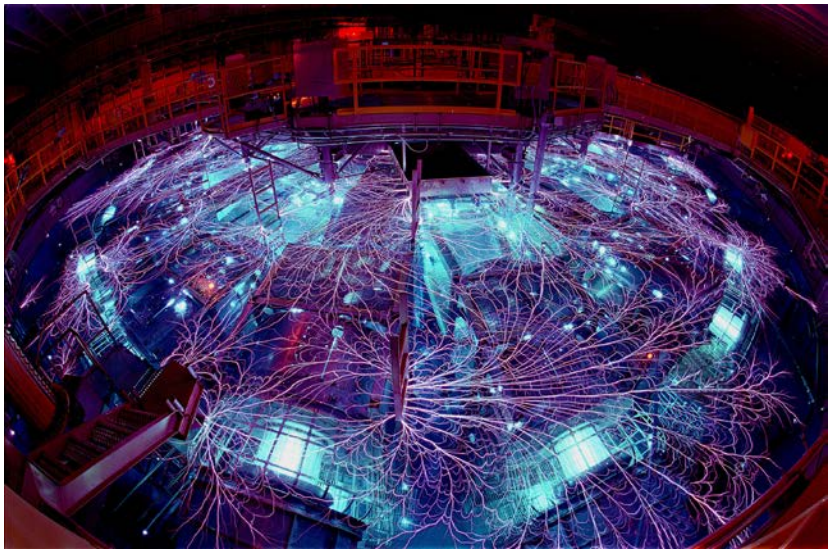
Inductor Needs Vary by Application





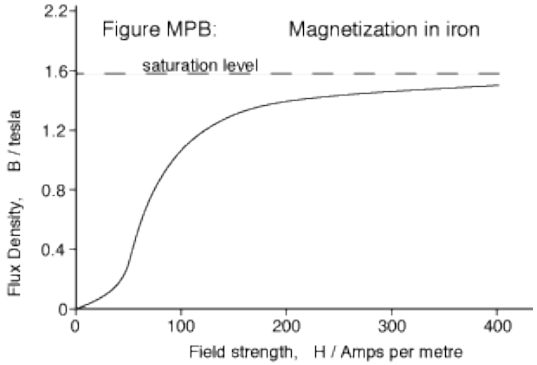
Z-machine, 20MA pulse

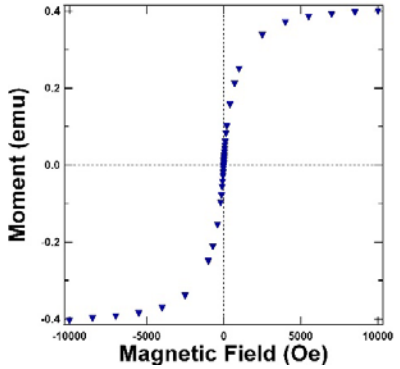
- Our interests include power electronics and pulsed power
- Frequencies of interest span from kHz to ~100MHz
- Can one material span this range?

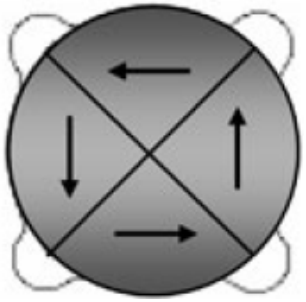
Superparamagnetism

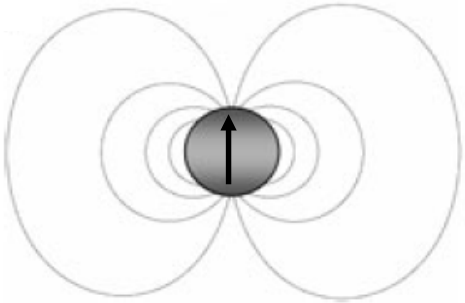
Superparamagnetic particles are single domain magnetic particles whose electron spins are aligned into a single giant moment.

Below a certain size (~40 nm diameter) the energy required to create a domain wall becomes larger than the decrease in energy the particle would experience through minimizing flux leakage.





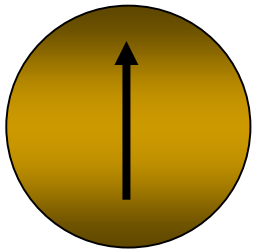




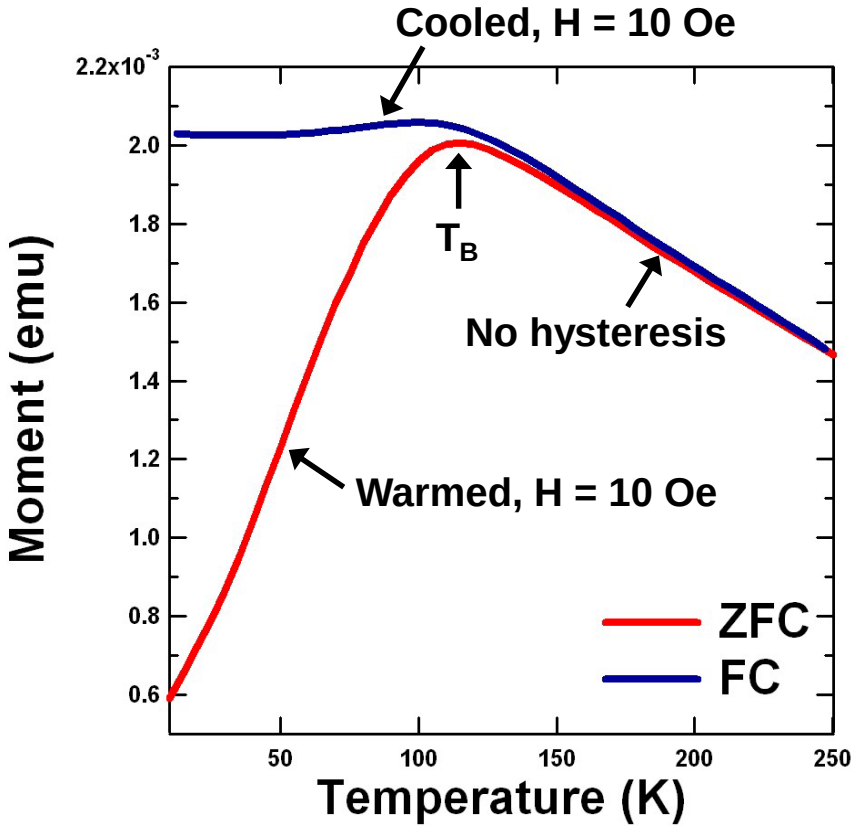
Blocking Temperature

Blocking Temperature (T_B): Point where a particle's dipole can reorient in the timescale of an experiment (100 s).

- T_B is directly dependent upon the product of the magnetocrystalline anisotropy and particle volume.
- Above the T_B particles are superparamagnetic (no hysteresis).
- Below T_B they are ferromagnetic (hysteresis, coercivity).
- Particle susceptibility (χ) has a maximum at T_B
- χ values much larger than multiple-domain particles ($\chi \leq 3$ for multiple-domain particles)

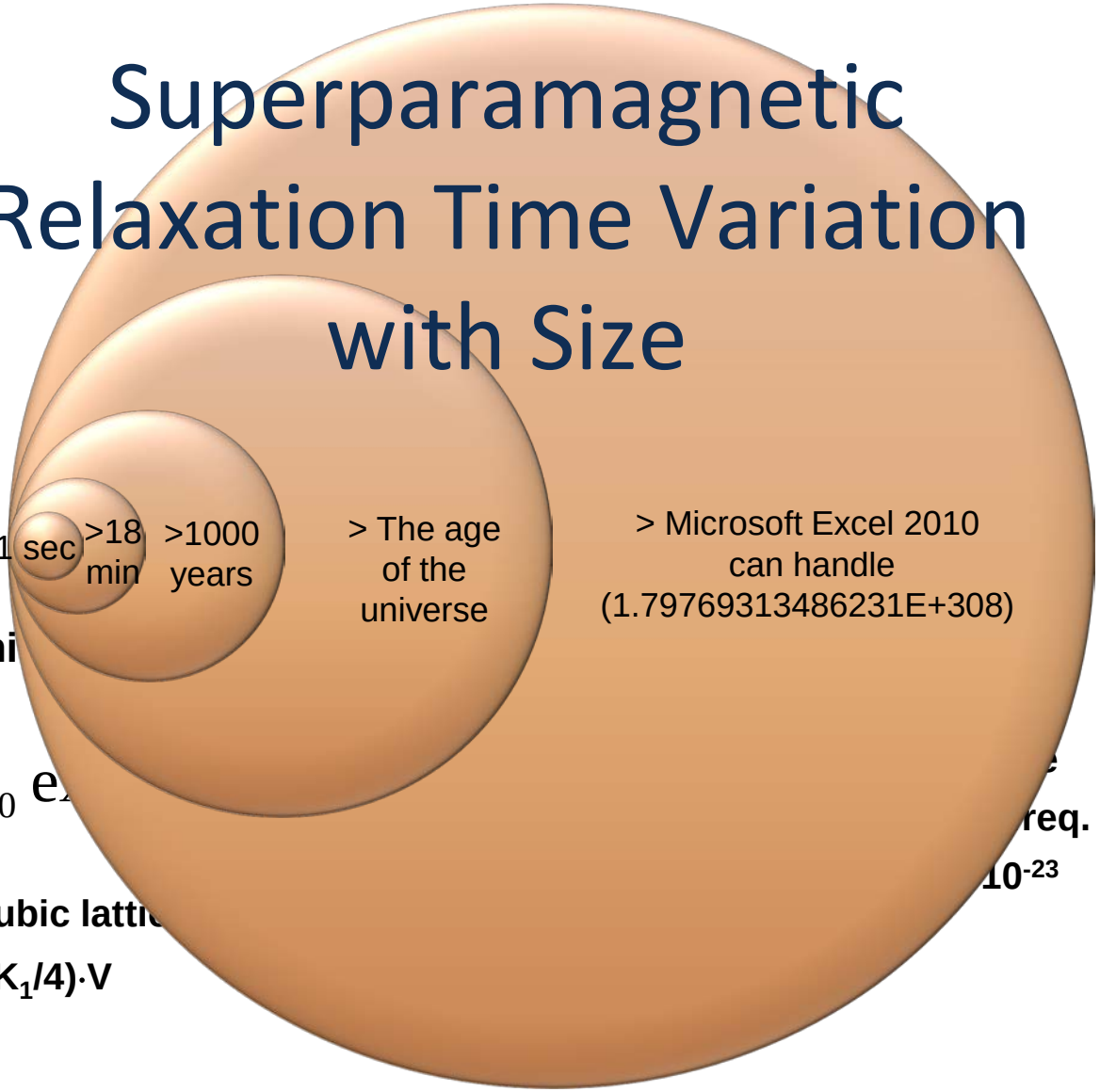


SQUID Magnetometry – Thermal Response



- ZFC: Zero field cooled
  - Cooled to low T while H = 0
  - Small field (H = 10 Oe) applied
  - Data collected as sample warms
- FC: Field cooled
  - Data collected while cooled to starting point
- Particles dispersed in frozen solvent, measuring Néel relaxation only (internal rotation of moment)
- T_B is maximum in ZFC data
- Double diameter, increase T_B by 8

Superparamagnetic Relaxation Time Variation with Size



Arrheni

$$\tau = \tau_0 \, e^{\dots}$$

req.

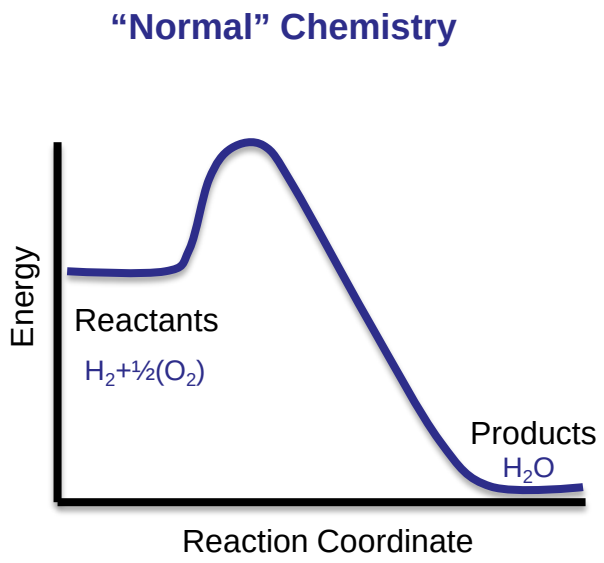
10^{-23}

In a cubic latti

$E_B = (K_1/4) \cdot V$

Nanoparticle Synthesis is Different

- In molecular chemistry, reactants form products in a thermodynamically stable/metastable state.
- In nanoparticle synthesis, the thermodynamically stable state is a bulk material.
- Kinetics govern nanoparticle synthesis.
- Since the reactions are kinetically controlled, concentrations, solvents, temperatures, etc. are critical.



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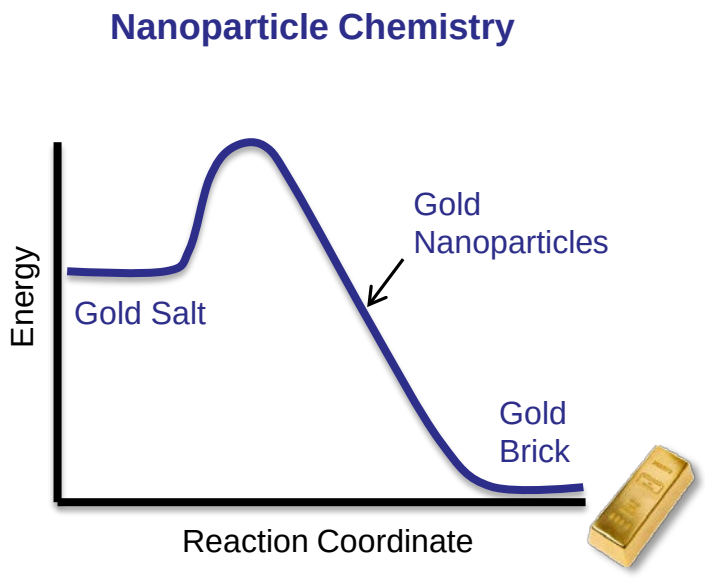
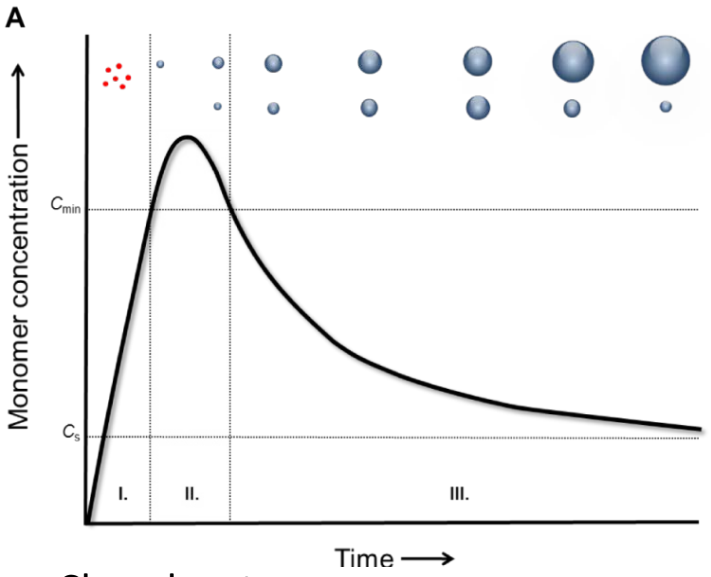
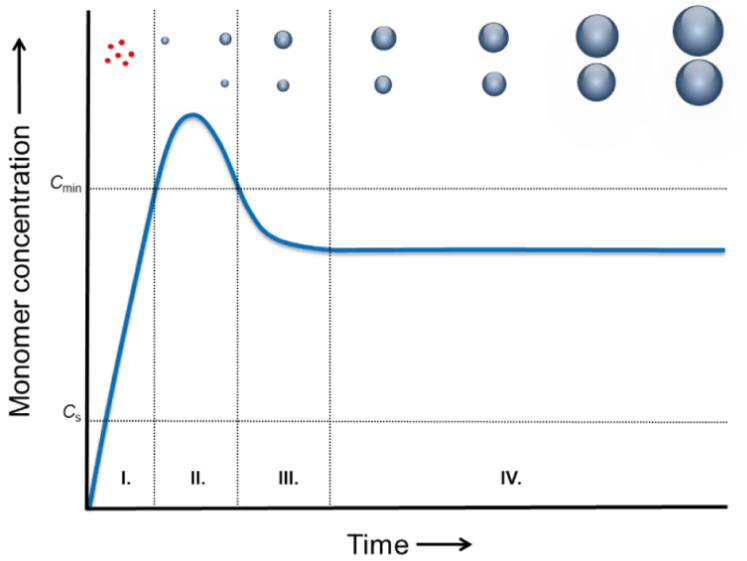


Extended LaMer

Classic LaMer



Extended LaMer

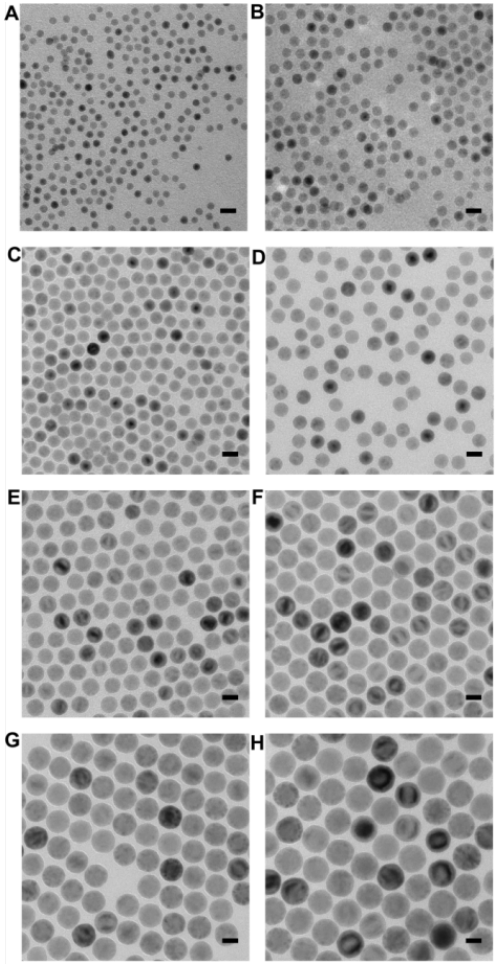


- Closed system
  - Eventual size at reaction completion is determined exclusively by the number of nuclei formed.
  - Nucleation is chaotic, non-linear and very hard to systematically control.

Lamer, V. K.; Dinegar, R. H., *J. Am. Chem. Soc.* ***1950, 72 (11), 4847-4854.***

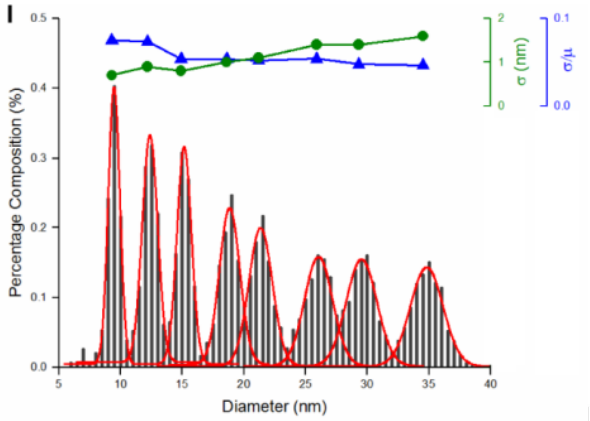
- Continuous Addition
  - Accept that nucleation can't be conveniently controlled.
  - Nucleate, then grow to appropriate size through precursor addition.

Vreeland, et al. *Chem. Mat.* ***2015, 27 (17), 6059-6066.***

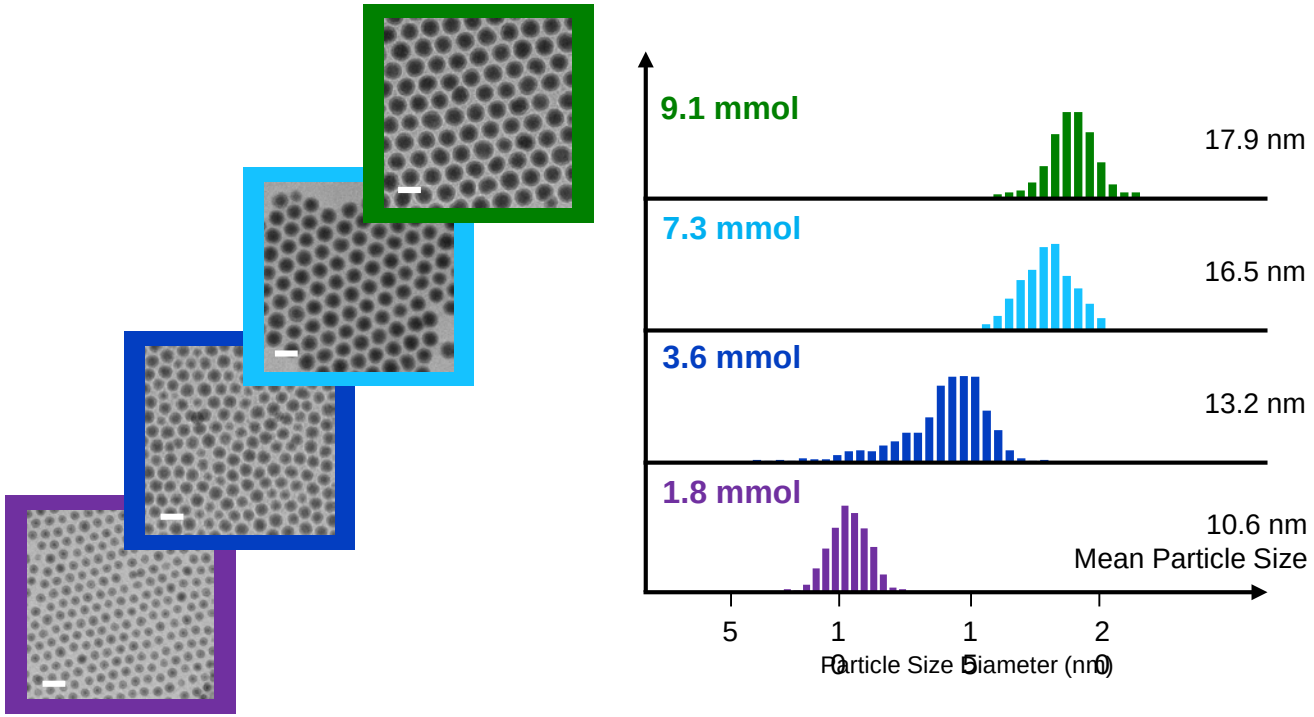


Reaction Results (Magnetite)

- Scale bars are 20 nm
- Aliquots are from a single reaction
- Particle are round and single crystal (HRTEM)
- Size focusing occurs early in the reaction

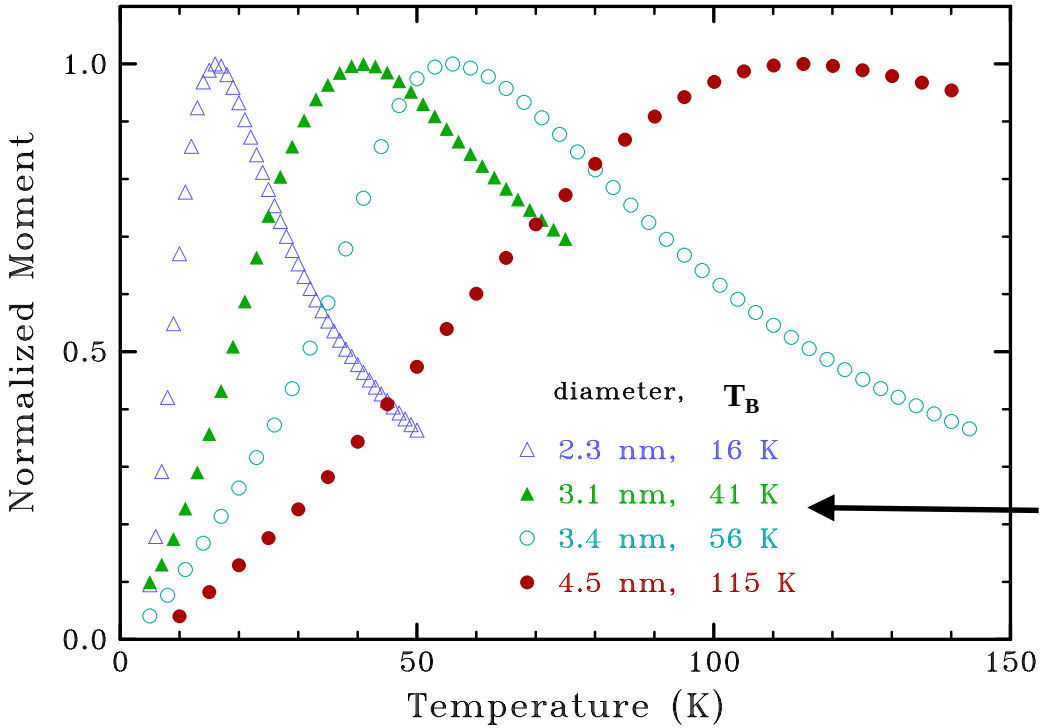


Extended LaMer Approach is General



- Fe (0) nanoparticles can be produced using the same continuous addition approach

T_B vs. Fe Nanoparticle Diameter



T_B scales with V

- All curves ZFC
- Broad peaks for larger particles expected
- Plotting σ vs. T/T_B peaks would superimpose

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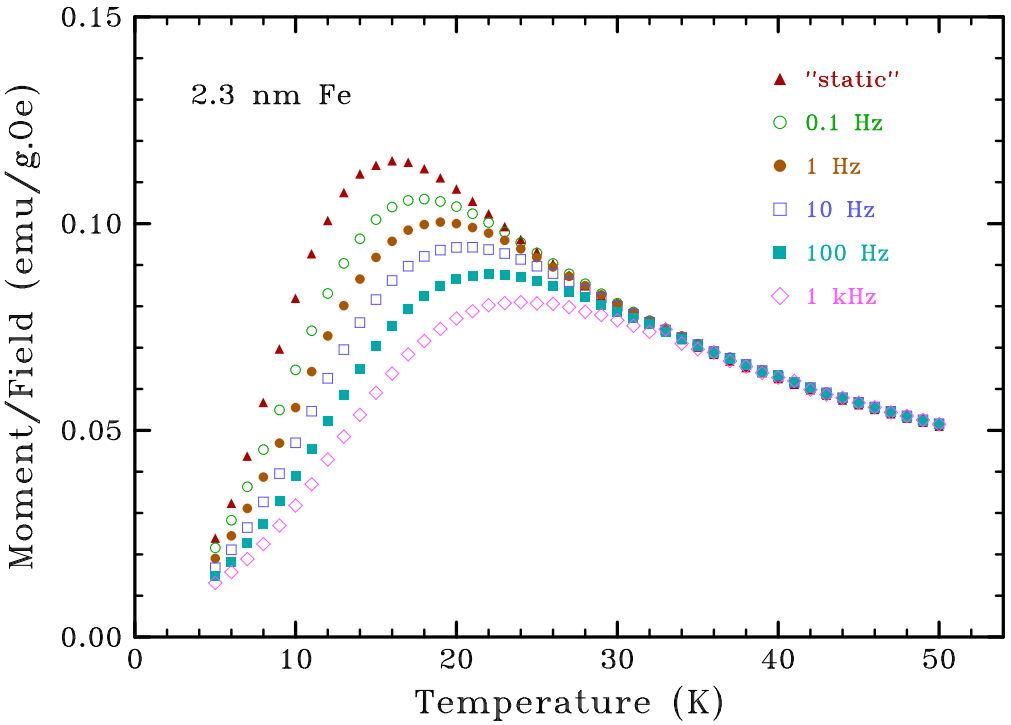
Fe Particle AC Magnetic Response



- **Spin reorientation time is thermally activated**
- **AC measurements determine T_B vs. frequency**
- **“static” measurement time ~ 100 s (0.01 Hz)**

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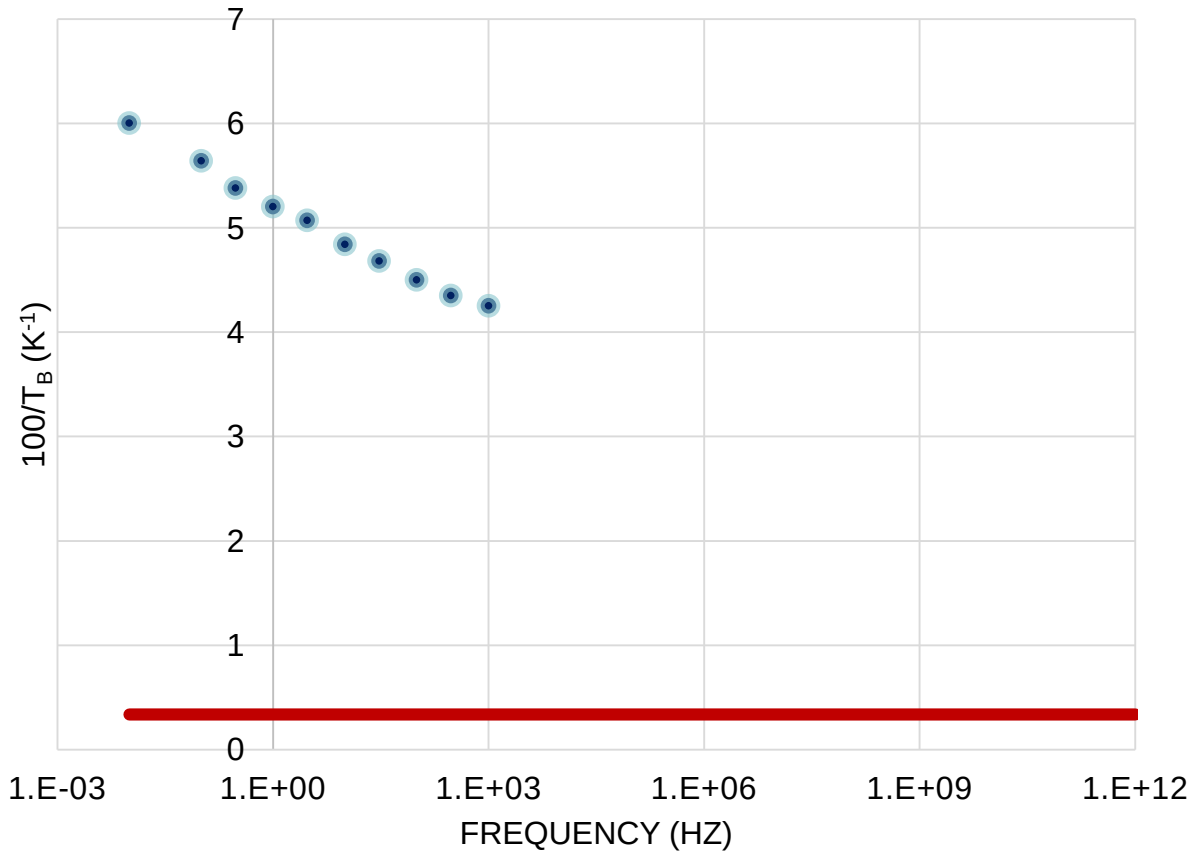
Time-Temperature Superposition



- Terminology borrowed from polymer science.
- For Arrhenius kinetics, higher temperature is equivalent to longer times.
- Can build a master curve from different instruments, using different temperatures and different frequencies.
- On or below the line, particles are unblocked and superparamagnetic.
- 2.3 nm Fe particles would be unblocked at room temperature at 1THz.

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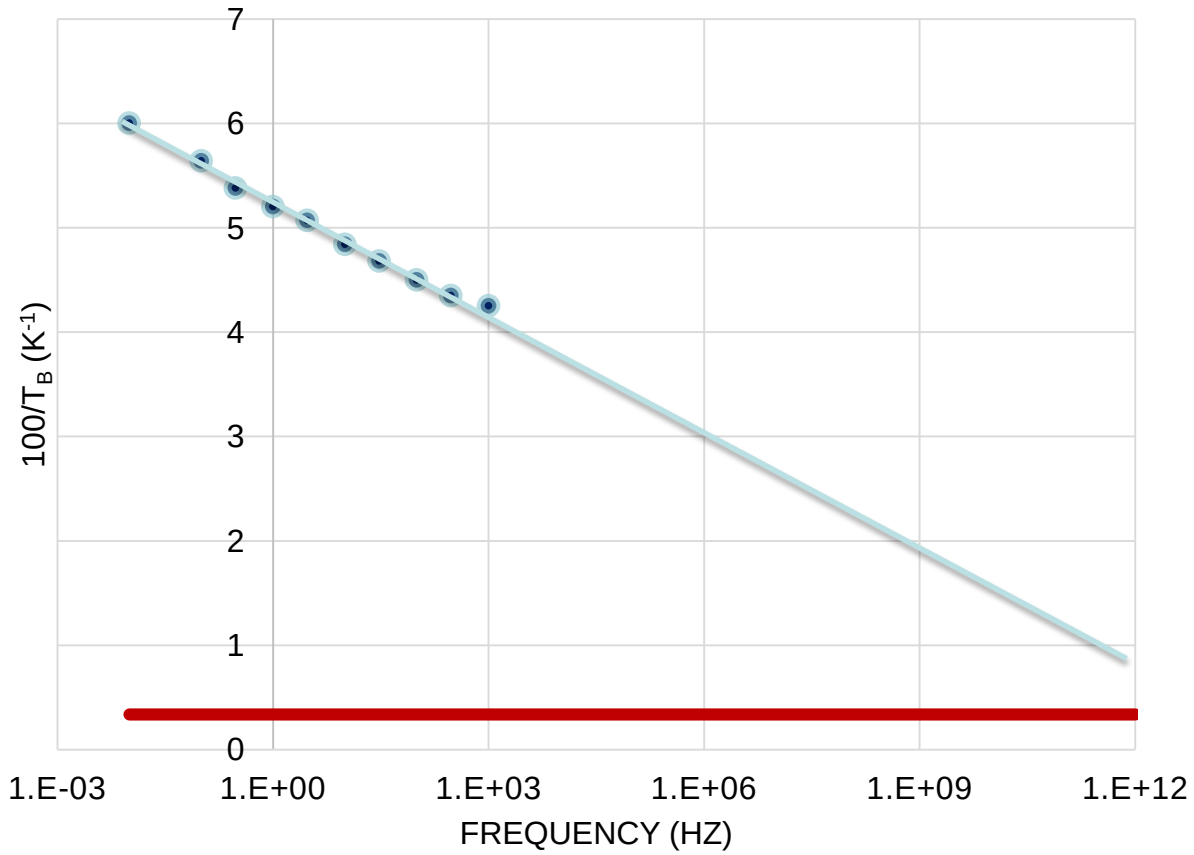

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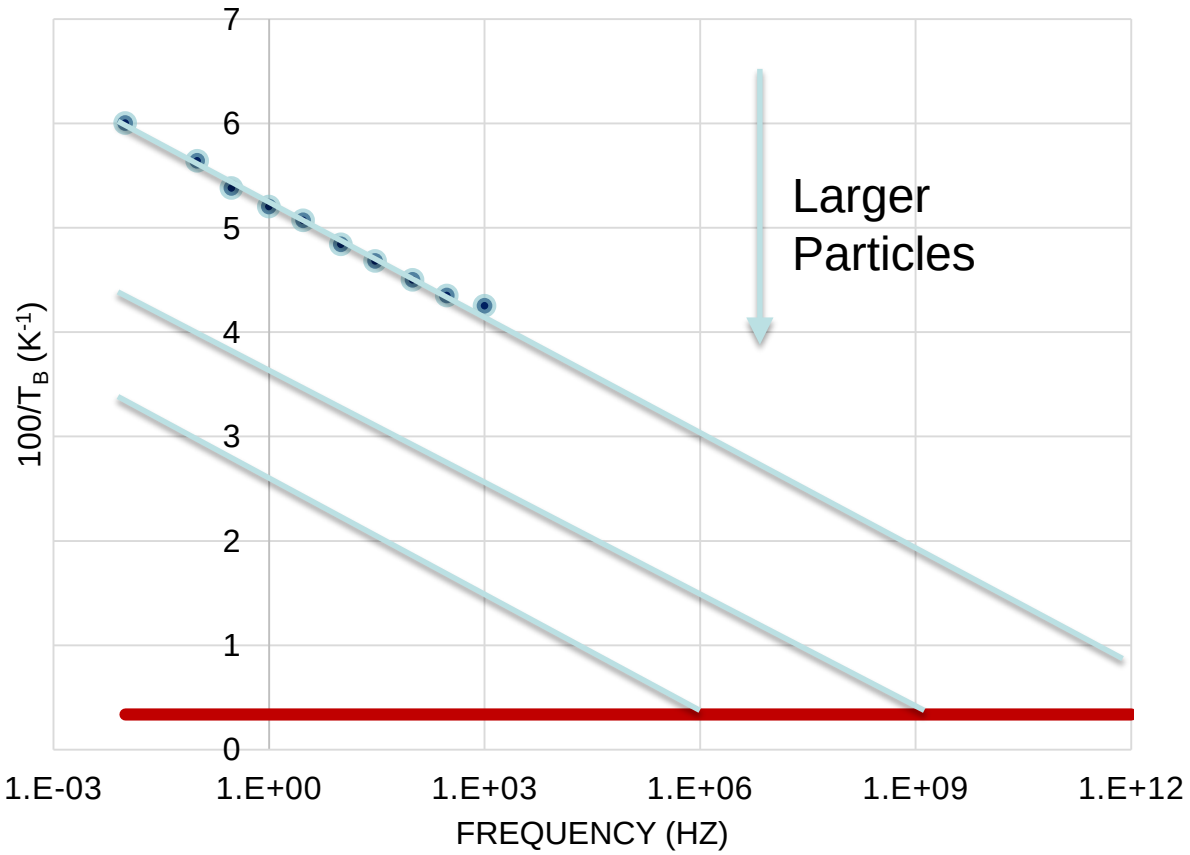

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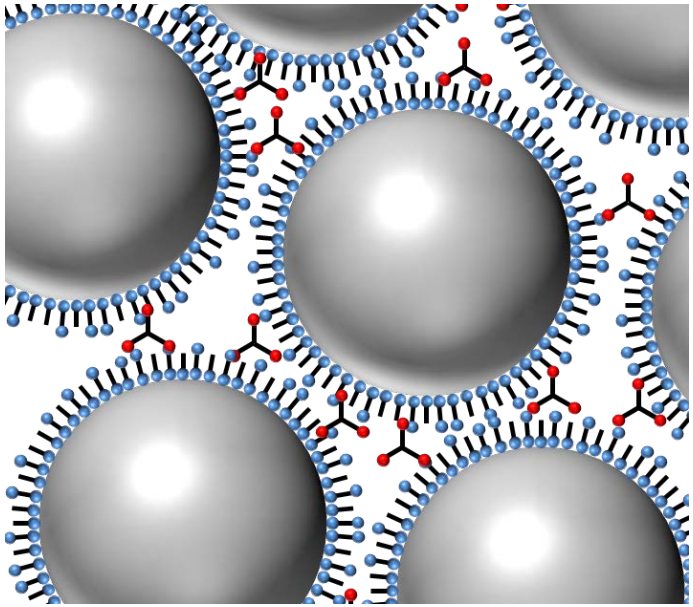
Constructing an Ideal Nanocomposite Inductor



- Need to assemble particles into a real material
- Account for interparticle interactions
  - can be treated as an effective anisotropy

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