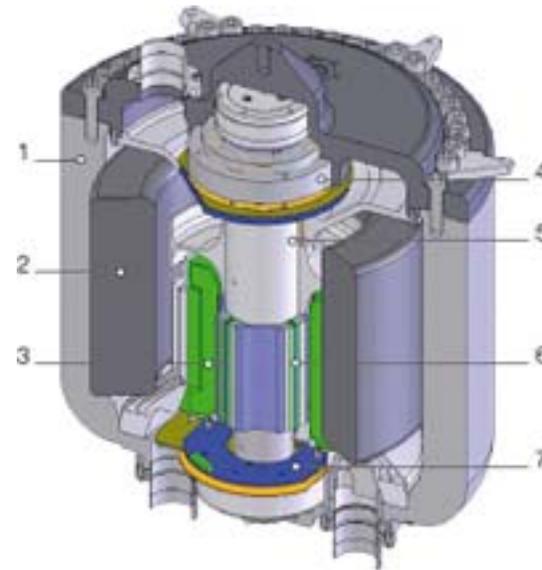


# Magnetic composites for flywheel energy storage

September 27, 2012

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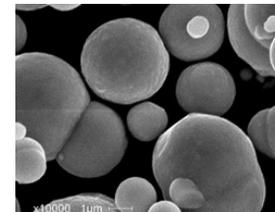
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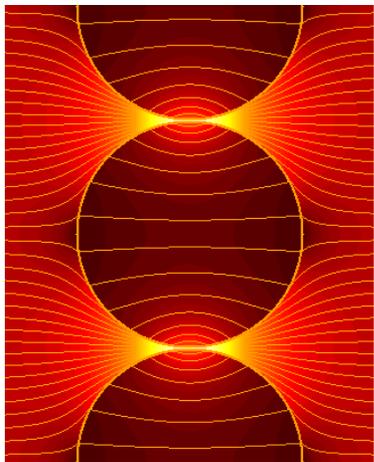
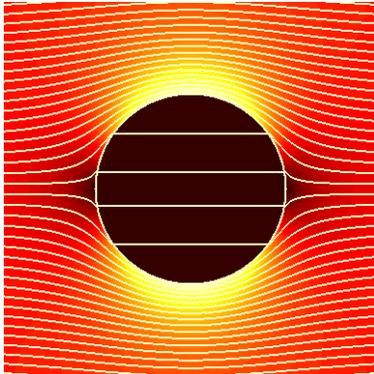
# Project description

- The bearings currently used in energy storage flywheels dissipate a significant amount of energy. Magnetic bearings would reduce these losses appreciably.
- Magnetic bearings require magnetic materials on an inner annulus of the flywheel for magnetic levitation.
- This magnetic material must be able to withstand a **2% tensile deformation**, yet have a reasonably high elastic modulus.
- This magnetic material must also be capable of enabling **large levitation forces**.
- Developing such a **soft magnetic composite** will enable much larger, more **energy efficient storage flywheels** that do not require a hub or shaft.
- Such composites are based on magnetic particles such as these:



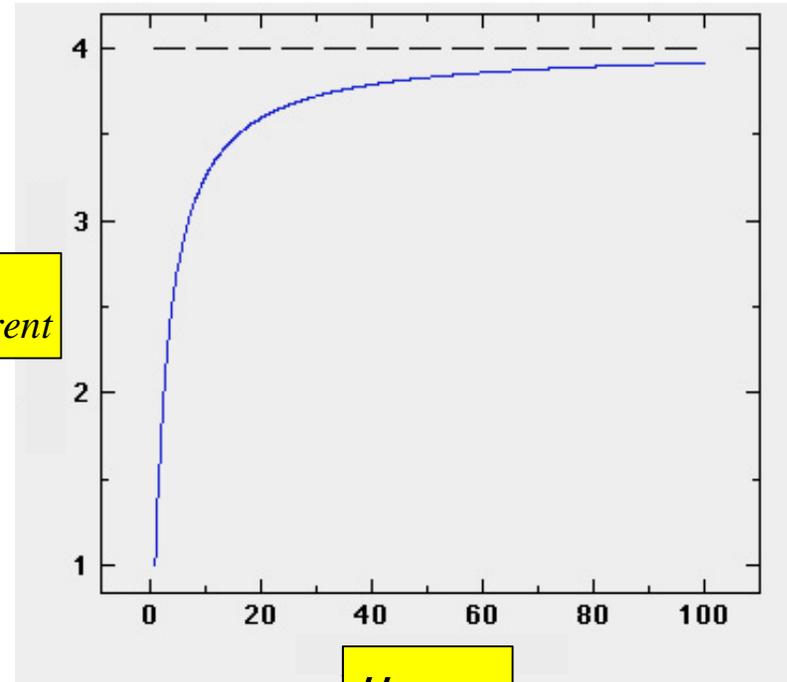
# The field exclusion problem

Particles **exclude** the magnetic field!



**Chaining** helps a bit.

$\mu_{\text{apparent}}$



$\mu_{\text{particle}}$

- The apparent permeability of an isolated sphere is **almost unrelated** to the permeability of the material of which it is composed.
- This is why random particle composites have disappointing permeabilities.

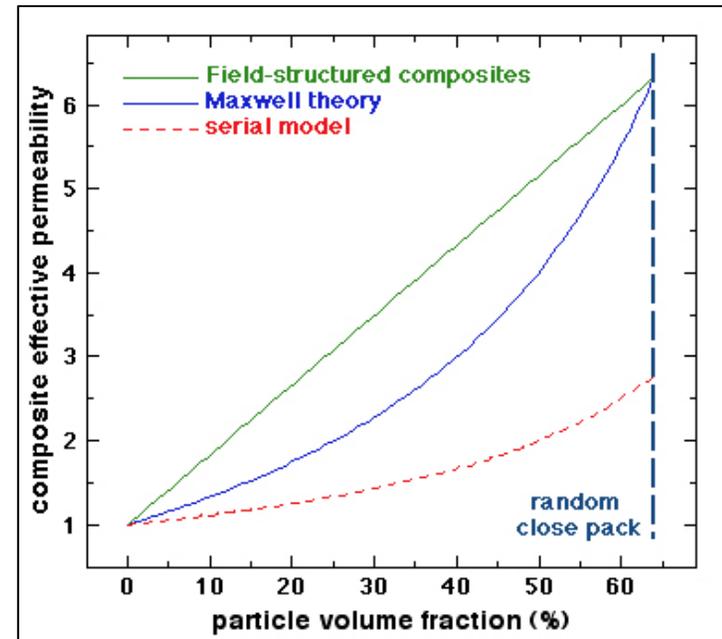
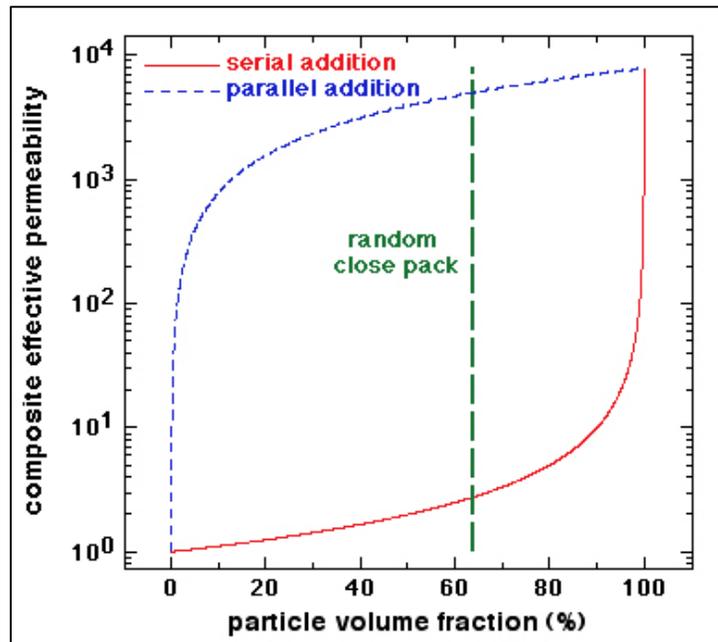
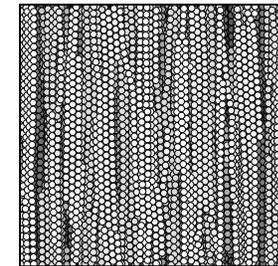
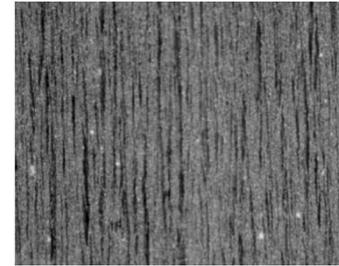
# Effective medium predictions

Series addition

parallel addition

$$\mu_{eff}^{-1} = \phi\mu_{Fe}^{-1} + (1-\phi)\mu_{poly}^{-1}$$

$$\mu_{eff} = \phi\mu_{Fe} + (1-\phi)\mu_{poly}$$

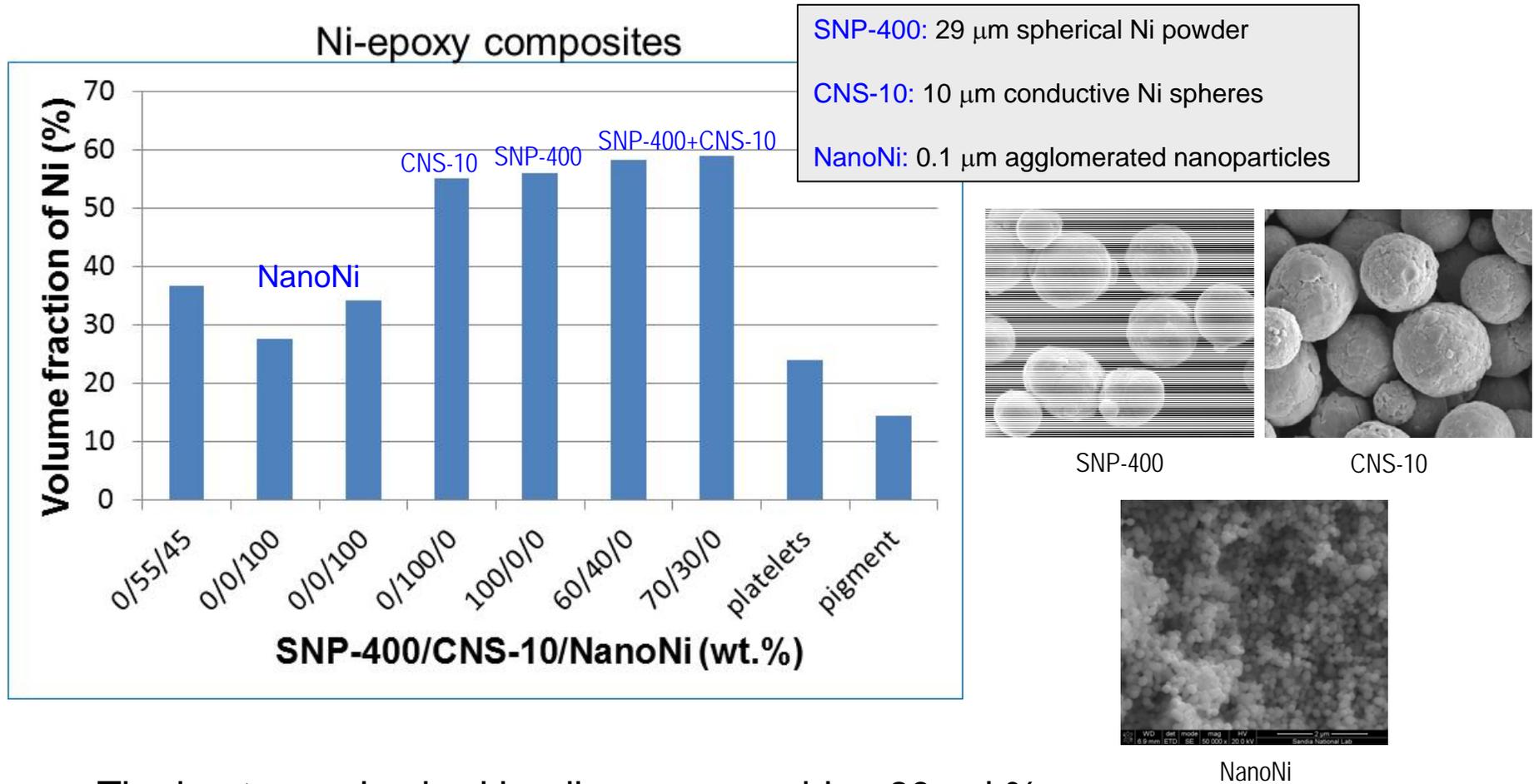


- The [series addition model](#) is much closer to experiment and more accurate effective medium theories.
- Creating a high permeability composite is very difficult! But is it necessary to do so?

# Approach

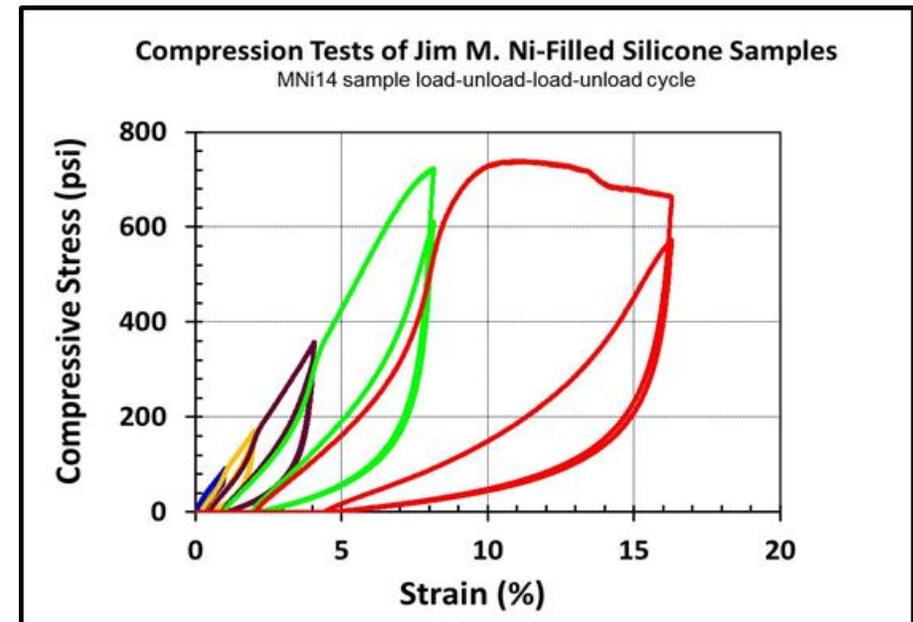
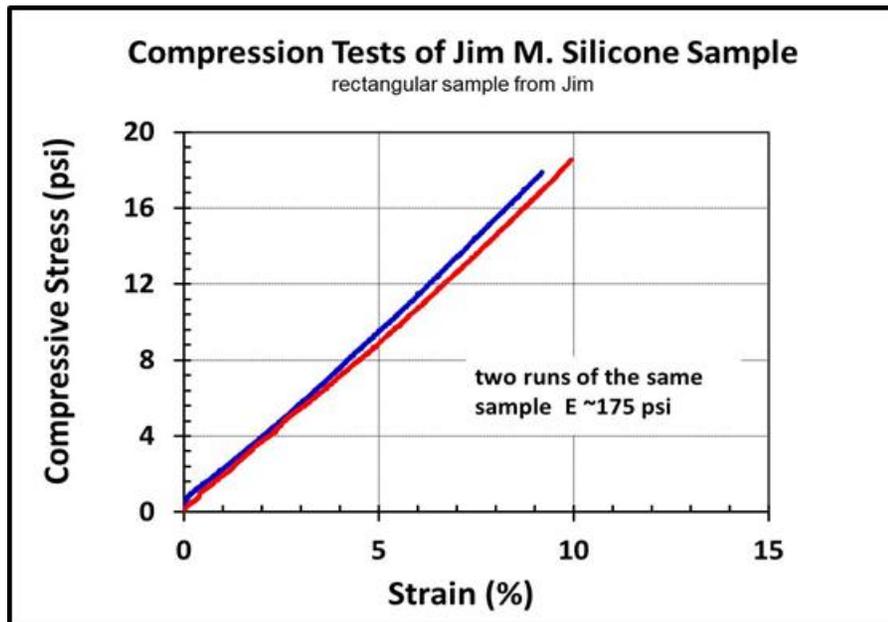
- Combine magnetic particles of differing sizes to create a sufficiently dense solid that the field is **forced to penetrate** the particles.
  1. Mix the particles with a “vortex” magnetic field.
  2. Add the mixture to a polymer and degas.
  3. Centrifuge the dense mixture in a swinging bucket rotor.
  4. Remove excess polymer, restir, and recentrifuge.
  5. Cure the dense solid and characterize the **magnetic** and mechanical properties.

# Mixed particle composites



- The best samples had loadings approaching 60 vol.%.
- Nanopowder composites did not have high loadings because of agglomeration.

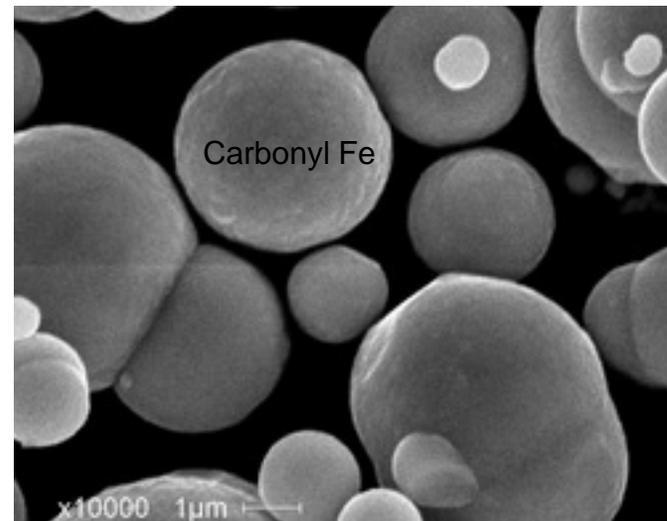
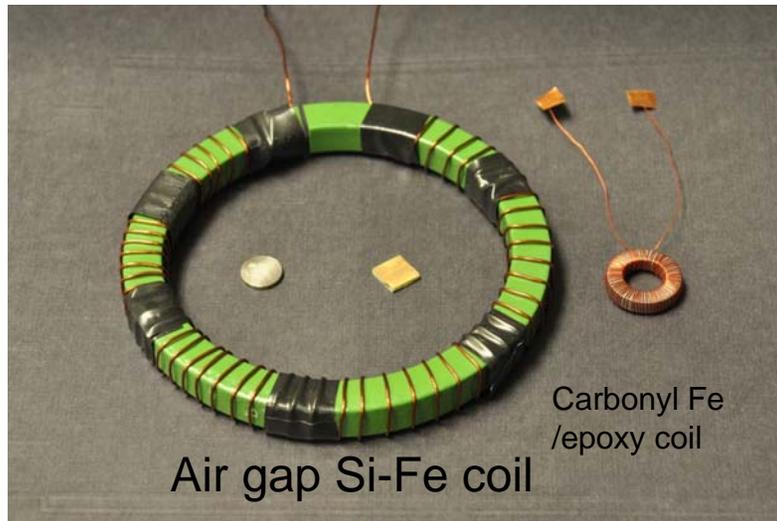
# Compression tests of silicone composites



- The modulus of the magnetic composites is  $\sim 10,000$  psi, which is  $\sim 60X$  that of the silicone polymer.
- Yield strain was 10%, but strains as high as 16% did not result in failure.
- The samples are conditioned to a higher strain after one cycle.

# Magnetic permeability measurements

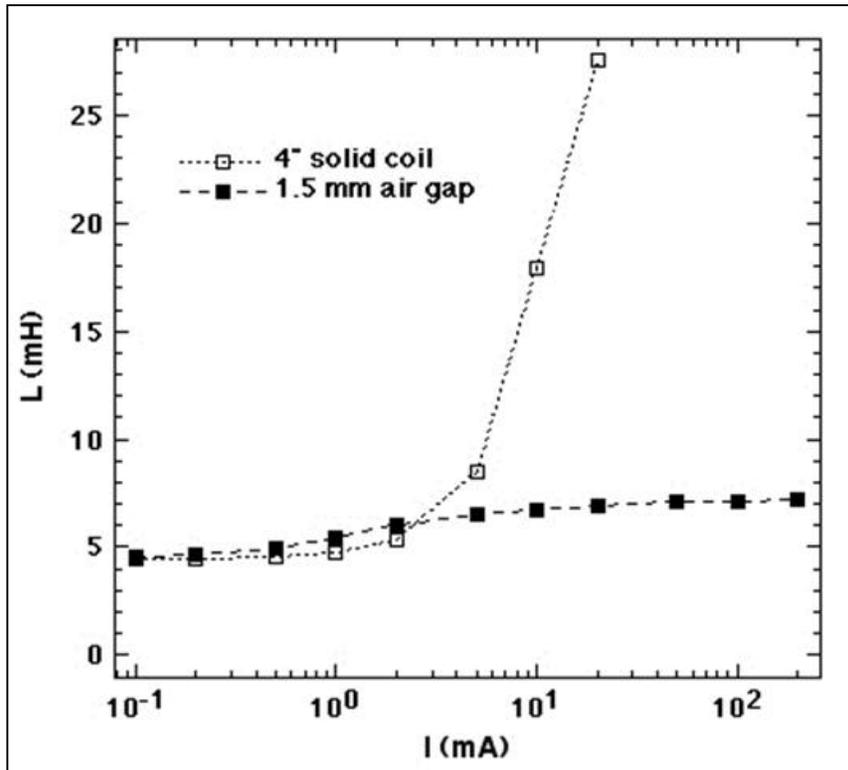
$$L (\mu H) = 0.0117h \log(d_{out} / d_{in}) \times \mu_r$$



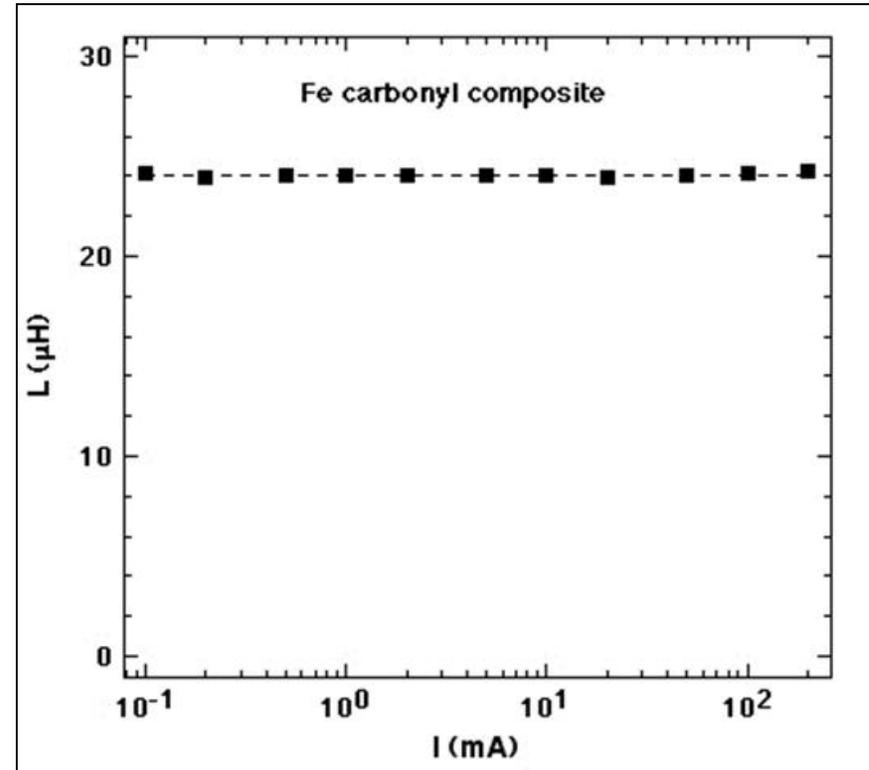
- The inductances of the composite coils were measured as a function of **drive current and frequency**.
- The magnetic permeability was computed from the inductance.

# Our composites show ideal magnetism

Conventional Si-Fe



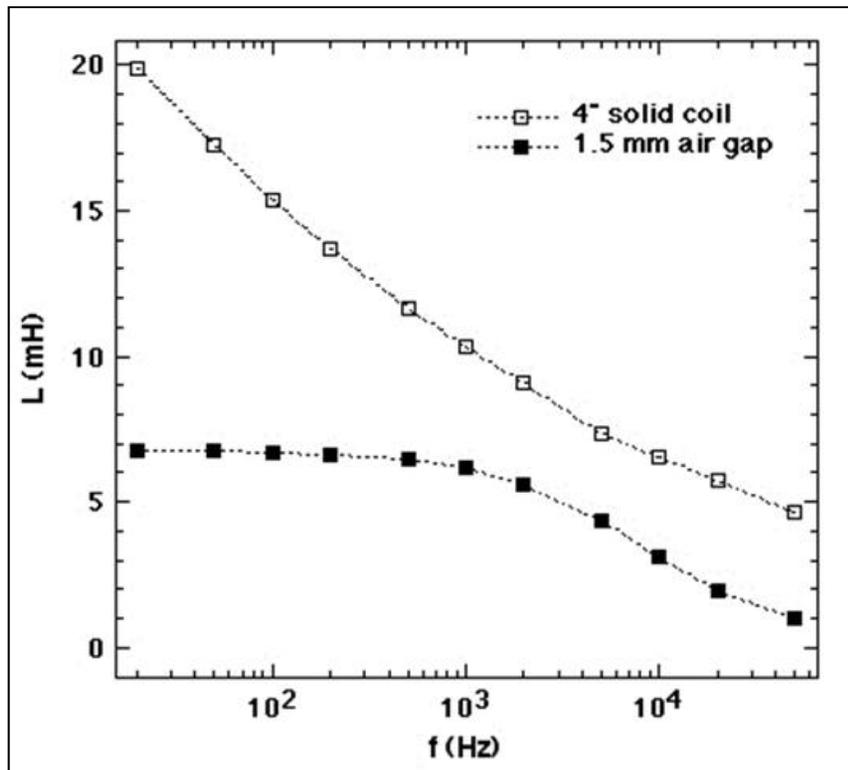
Our carbonyl Fe composite



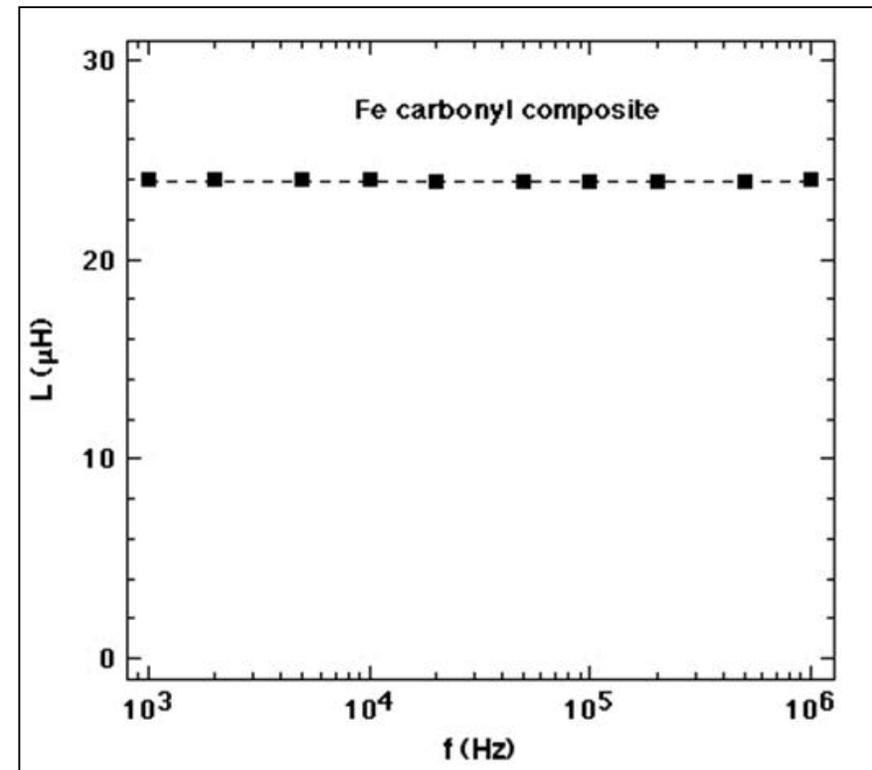
- The composite inductance is completely **independent of drive current** (field).
- Our best carbonyl Fe composite had a volume fraction of 56 vol.% and a **relative magnetic permeability of 13.0**.

# Our composites have a high bandwidth

Conventional Si-Fe

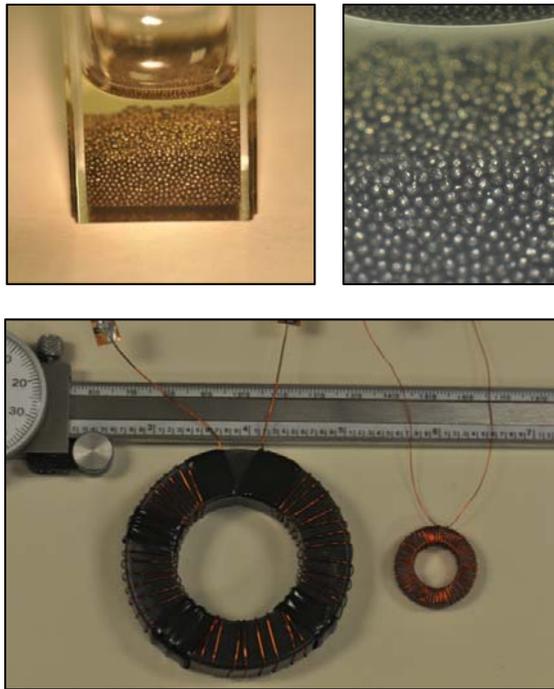


Our carbonyl Fe composite

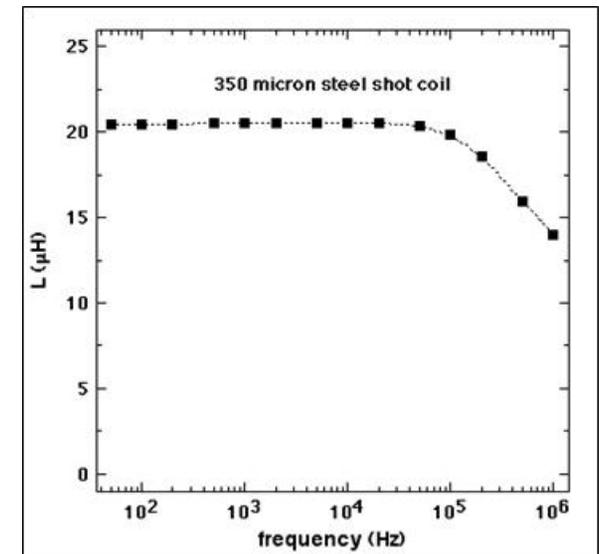
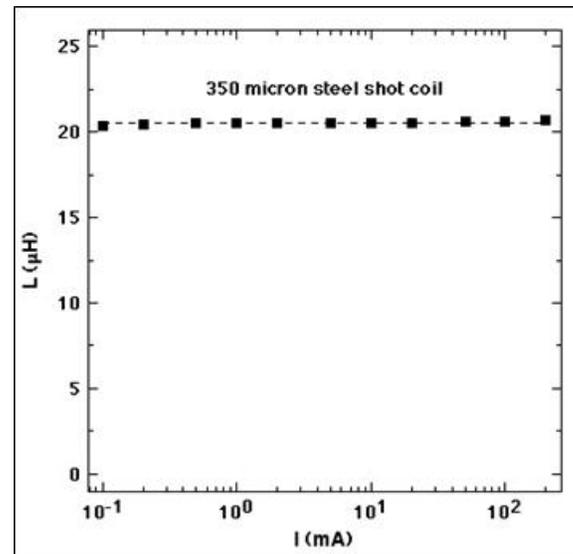


- The composite permeability has a response faster than  $1 \mu\text{s}$ !
- This rapid response facilitates feedback control in rapidly spinning flywheels.

# Cut-wire steel shot composites



Composites exhibit **linear magnetism** with a **fast response**.

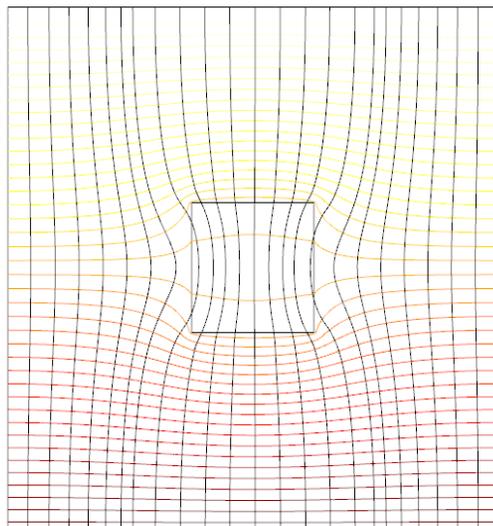


- The highly spherical steel shot gives a loading of **62.7 vol.%!**
- Our first coil demonstrated a **relative permeability of 13.1.**
- Our first attempt at mixing these particles with 4-7 micron carbonyl Fe gave a loading of **70.0 vol.%.**
- These materials will be the basis of **exceptional magnetic composites.**

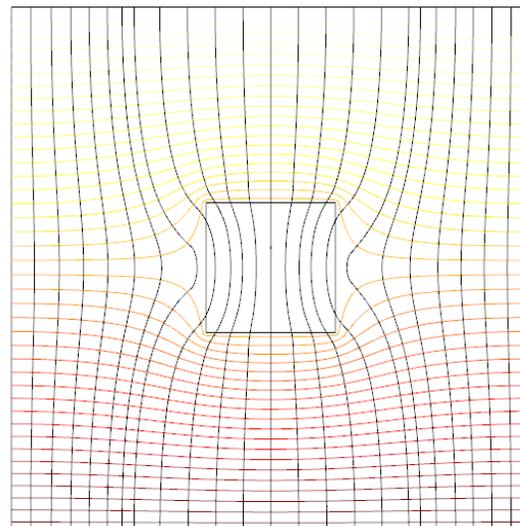
# Magnetic force on a composite

$$\text{Kelvin force: } \mathbf{F} = -\mathbf{M}\nabla\mathbf{H}$$

permeability = 10

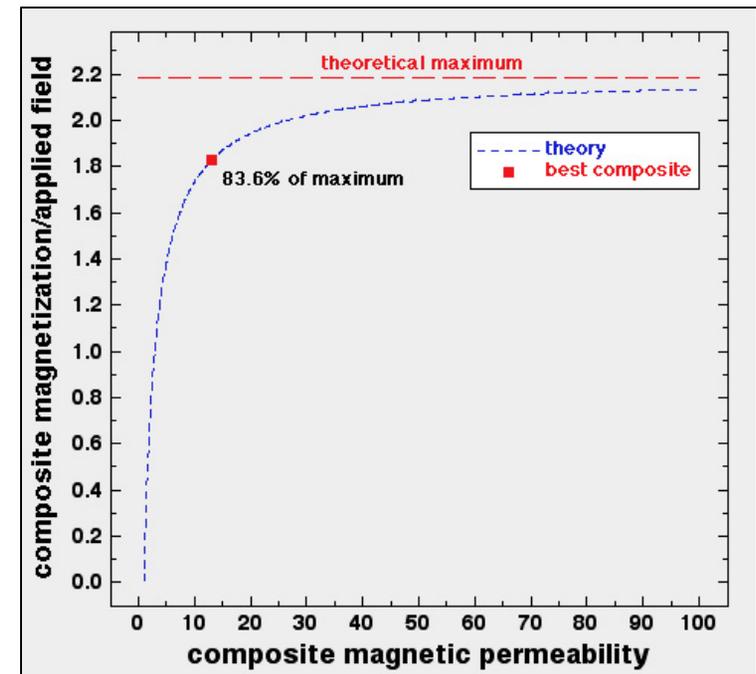


permeability = 100



The flux density through the magnetic composite is essentially identical in these two cases!

The composite magnetization saturates!



- The magnetization of a body is a **strong function of its shape**.
- In this field geometry our composite gives a magnetic force **~84%** of maximum.

# Summary/Conclusions

- We have developed **highly accurate methods** for measuring the magnetic permeability of dense composites.
- Composite magnets made of soft silicone polymers exhibit **extremely high moduli**, yet **can tolerate >16% compressive strains**.
- Micron-size Fe particles give a relative **magnetic permeability of ~13.0**.
- Pure **350 micron steel shot** gives loadings slightly higher than that of carbonyl Fe and a comparable permeability.
- All of our composite magnets exhibit **ideal magnetism** and ultrafast **response**.
- Combining steel shot with carbonyl Fe gives **significantly higher loadings** (20% less void).

# Future Tasks

- **Modeling the magnetic levitation circuit** to understand how the normal force depends on the composite permeability in greater detail.
- **Develop mixed particle composites** based on monodisperse steel shot to appreciably increase the packing density and composite permeability.
- Produce composites in a geometry suitable for **direct tensile testing**.
- Couple this work closely to the needs of the flywheel industry.

# Contact Information

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