Harvard John A. Paulson School of Engineering and Applied Sciences

Billy Koech
EE SB '20

Soft EPMs: Design and Fabrication of Soft Composite Materials for Soft Elecro-magnetic Actuators

Pushing the limit of compliance

Presentation Structure

Background

Problem Statement

Technical Specifications

Design

Build

Measure

1. Ouline

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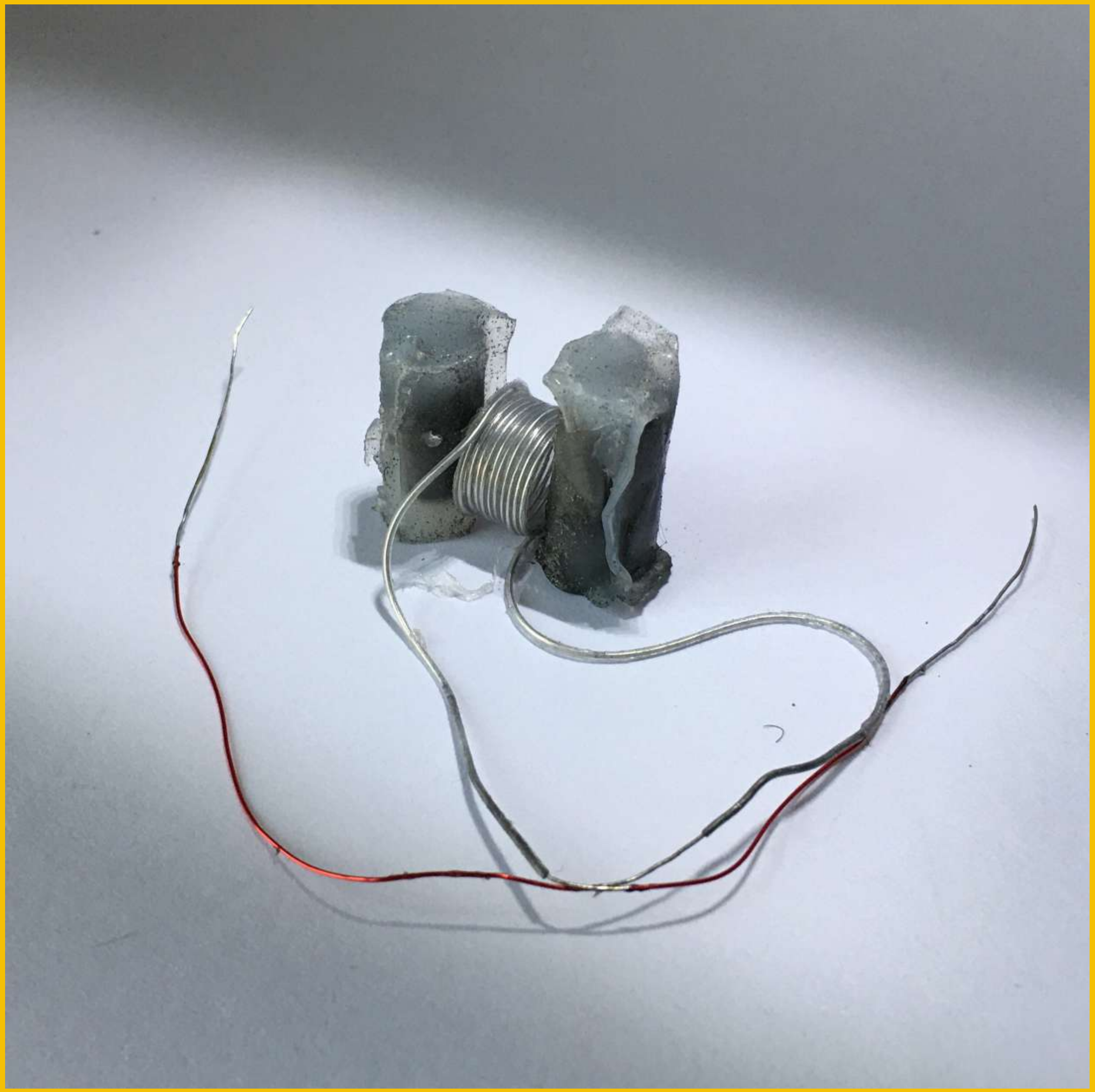
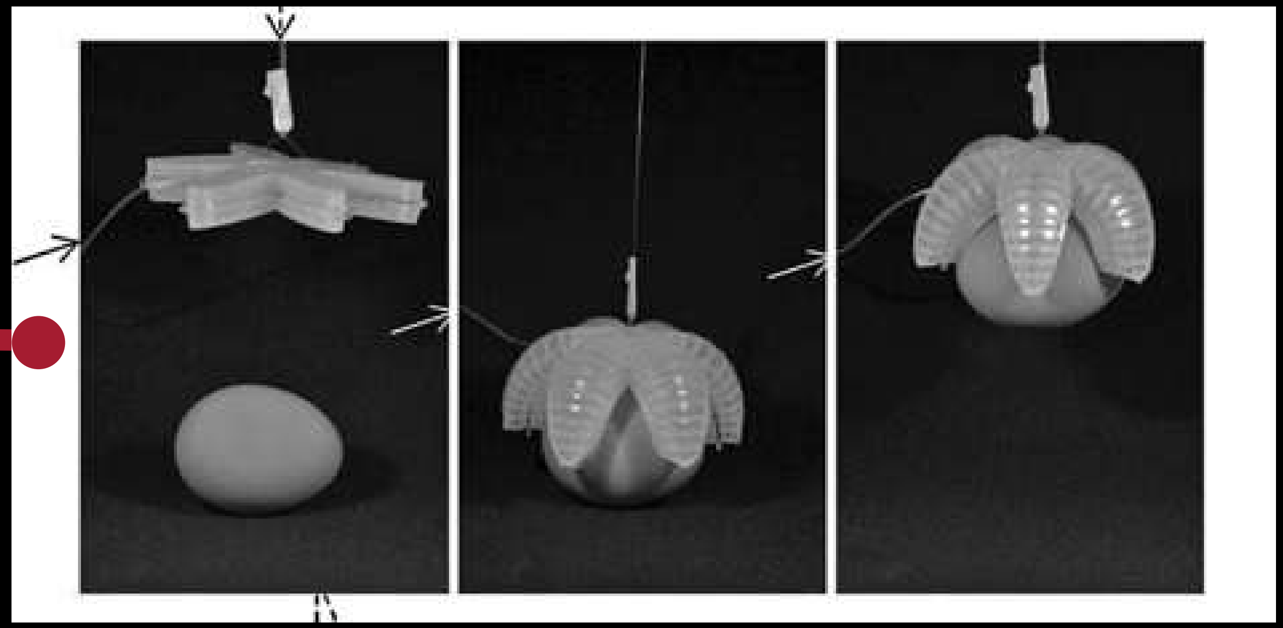


Define

Background

Actuation methods

Pneumatic

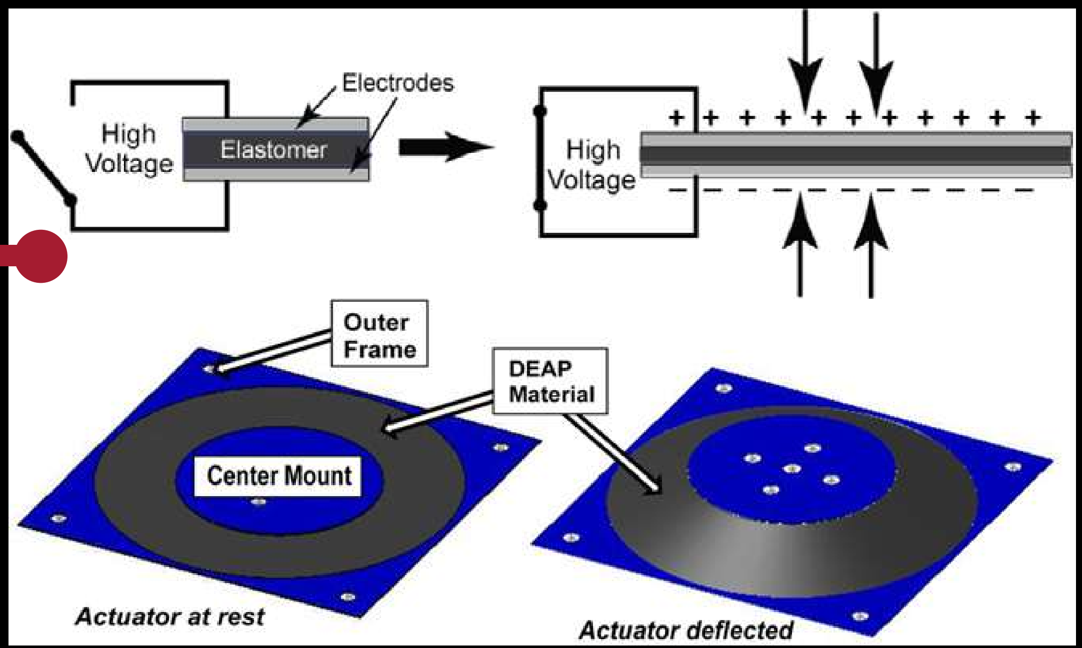


[1]

Shape memory alloys

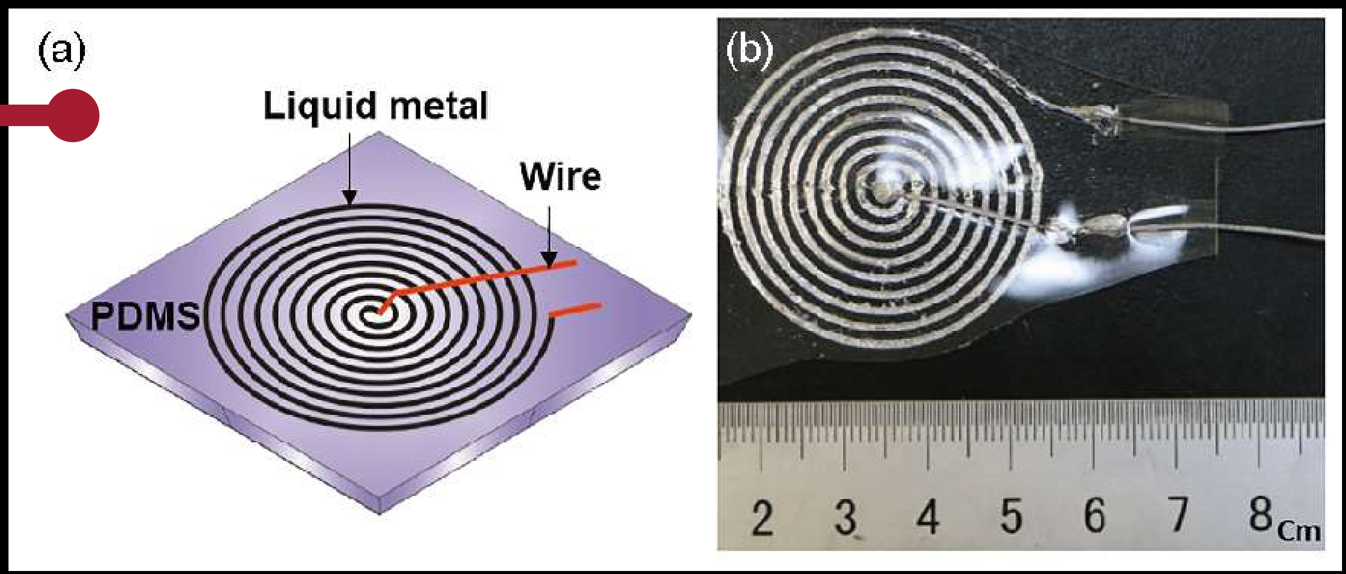
[2]

Dielectric-electro activated polymers



[3]

Magnetic/electromagnetic methods.

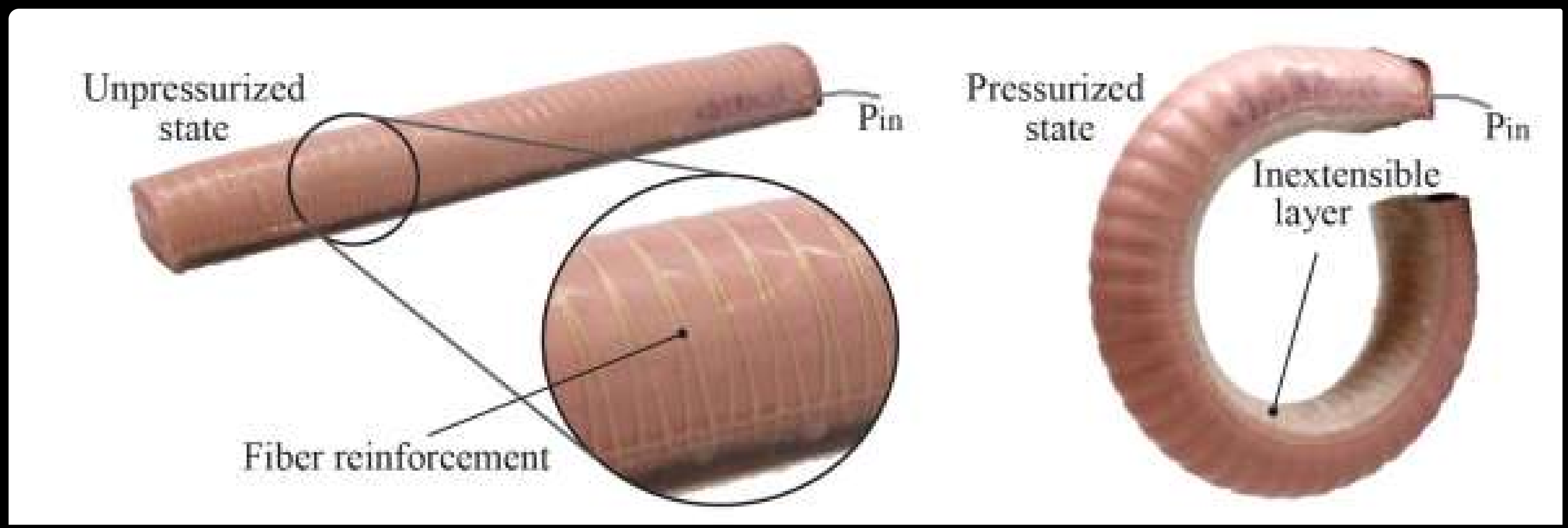


[4]

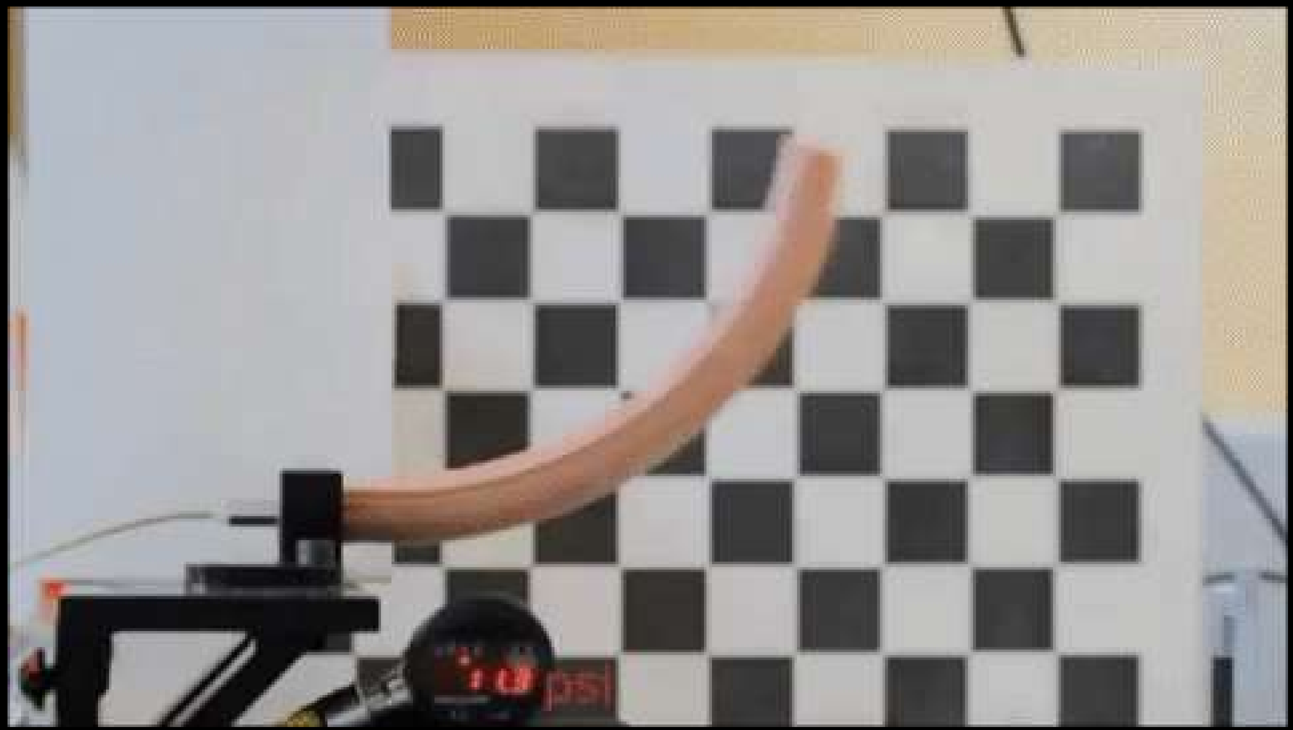
Background

Common Actuation methods [3]

Pneumatic

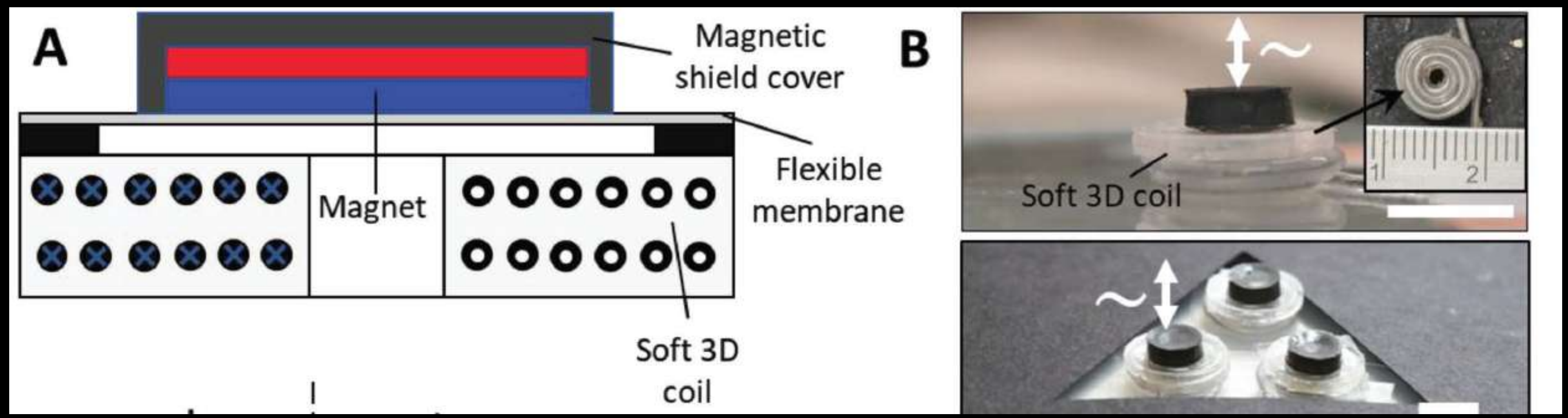


[1]



[1]

Magnetic/electromagnetic methods.



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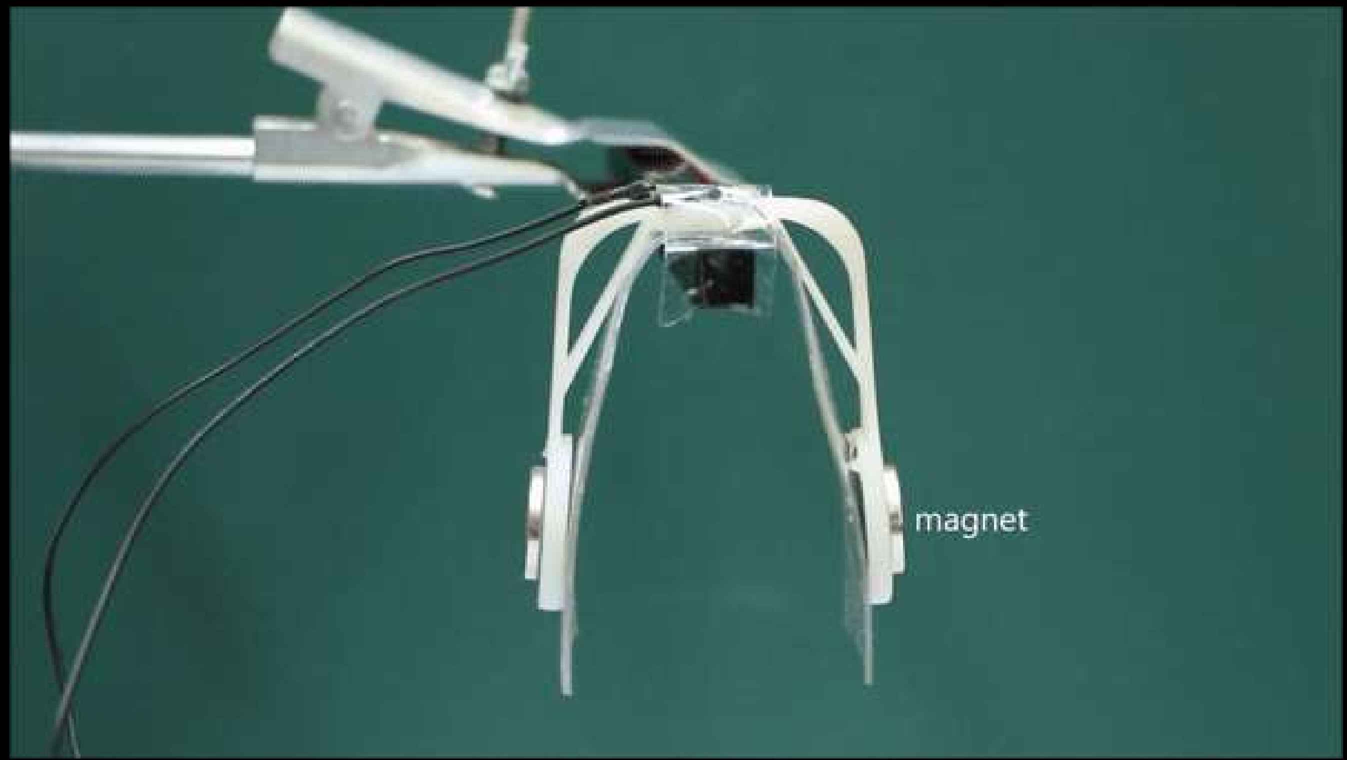

[4]

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Background

Pneumatic

Magnetic/electromagnetic methods.

Background

Challenges

Pneumatic

- Requires extensive pressure infrastructure for higher precision control [1]

Magnetic/electromagnetic methods.

- Rigid actuators
- High power consumption

Drives up fabrication and energy cost

Problem Statement

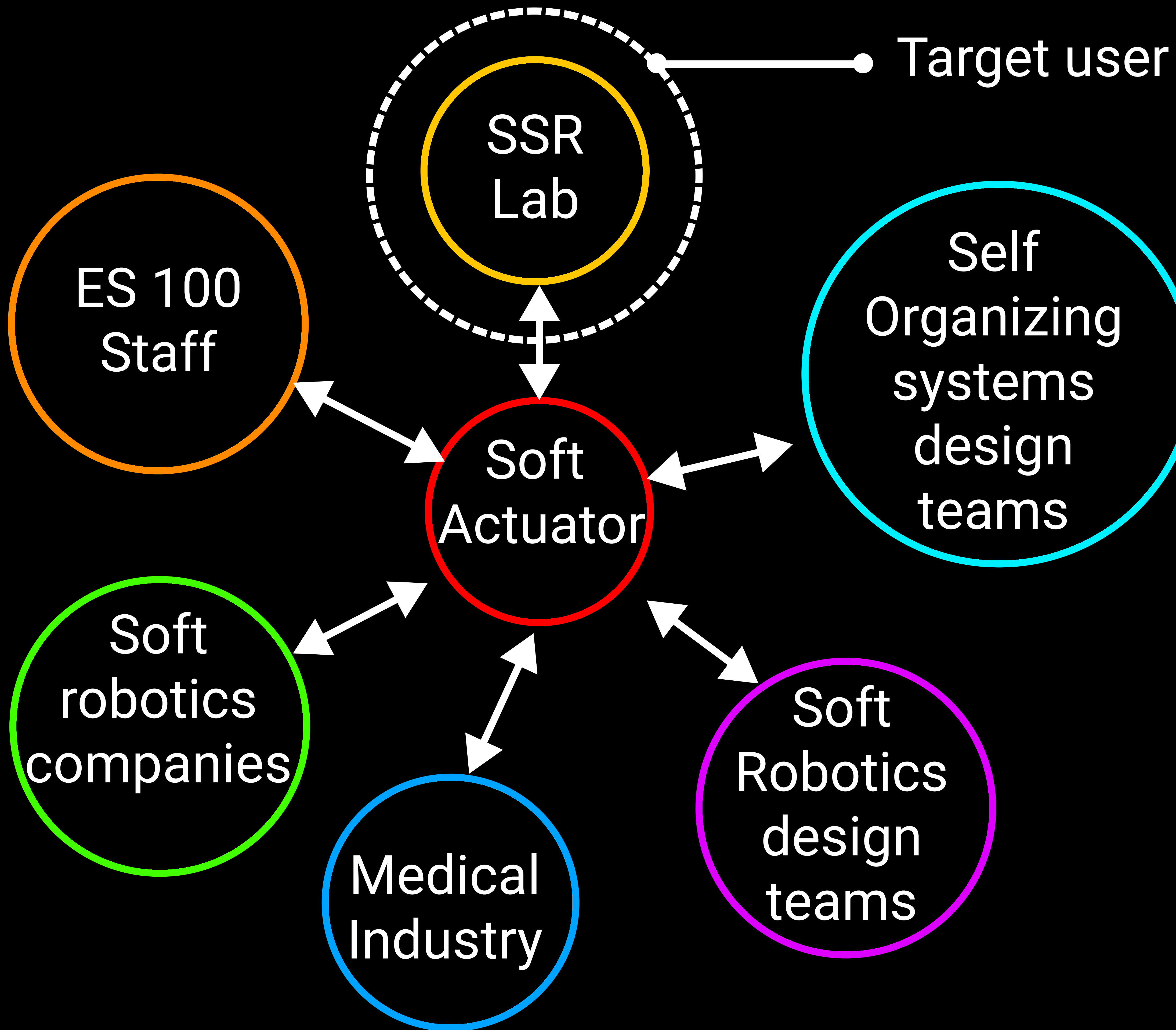
Pneumatic and electromagnetic methods are the most common methods of actuation in the field of soft robotics, however, pneumatic methods require extensive pressure networks in order to achieve high precision control on smaller scales, while most electromagnetic actuators exist in rigid form with high power consumption rates

6. Define

Problem Statement

Pneumatic and electromagnetic methods are the most common methods of actuation in the field of soft robotics, however, pneumatic methods require extensive pressure networks in order to achieve high precision control on smaller scales, while most electromagnetic actuators exist in rigid form with high power consumption rates Therefore there is a need for a soft actuator with high precision control at low energy costs.

Stakeholder Map



8. Define

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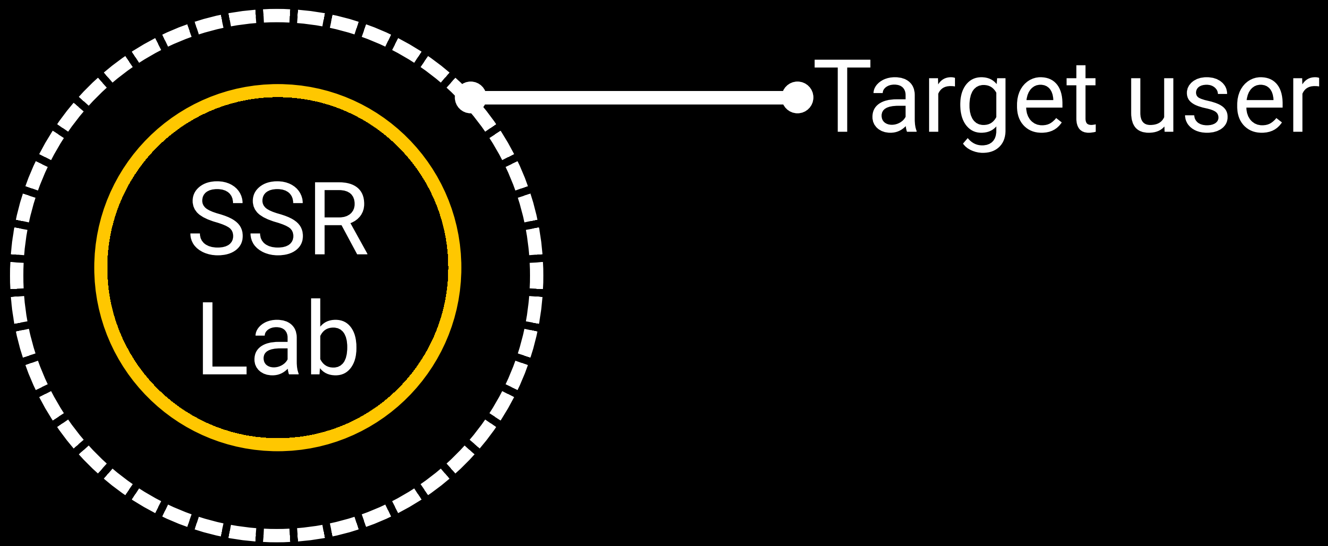
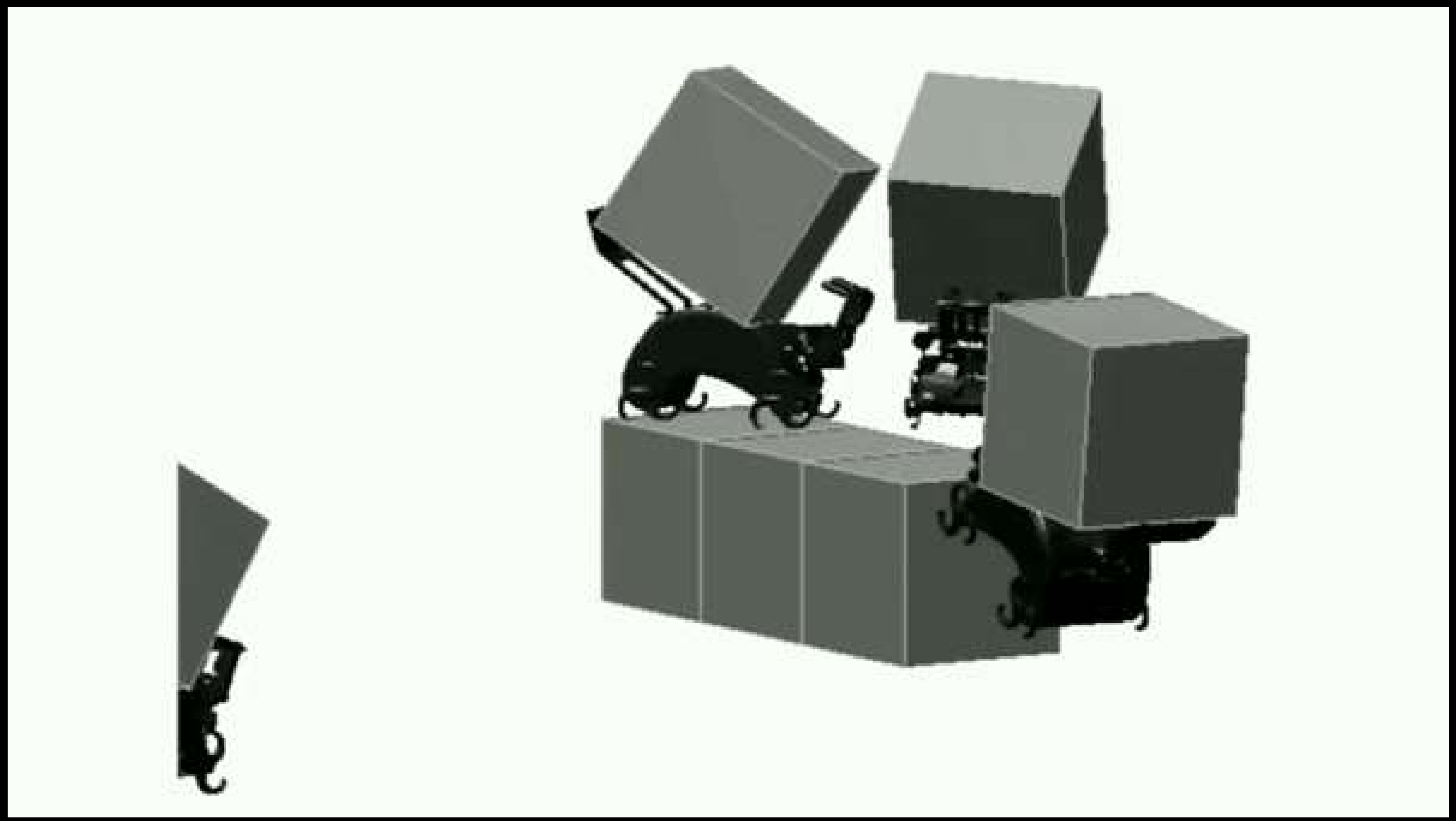
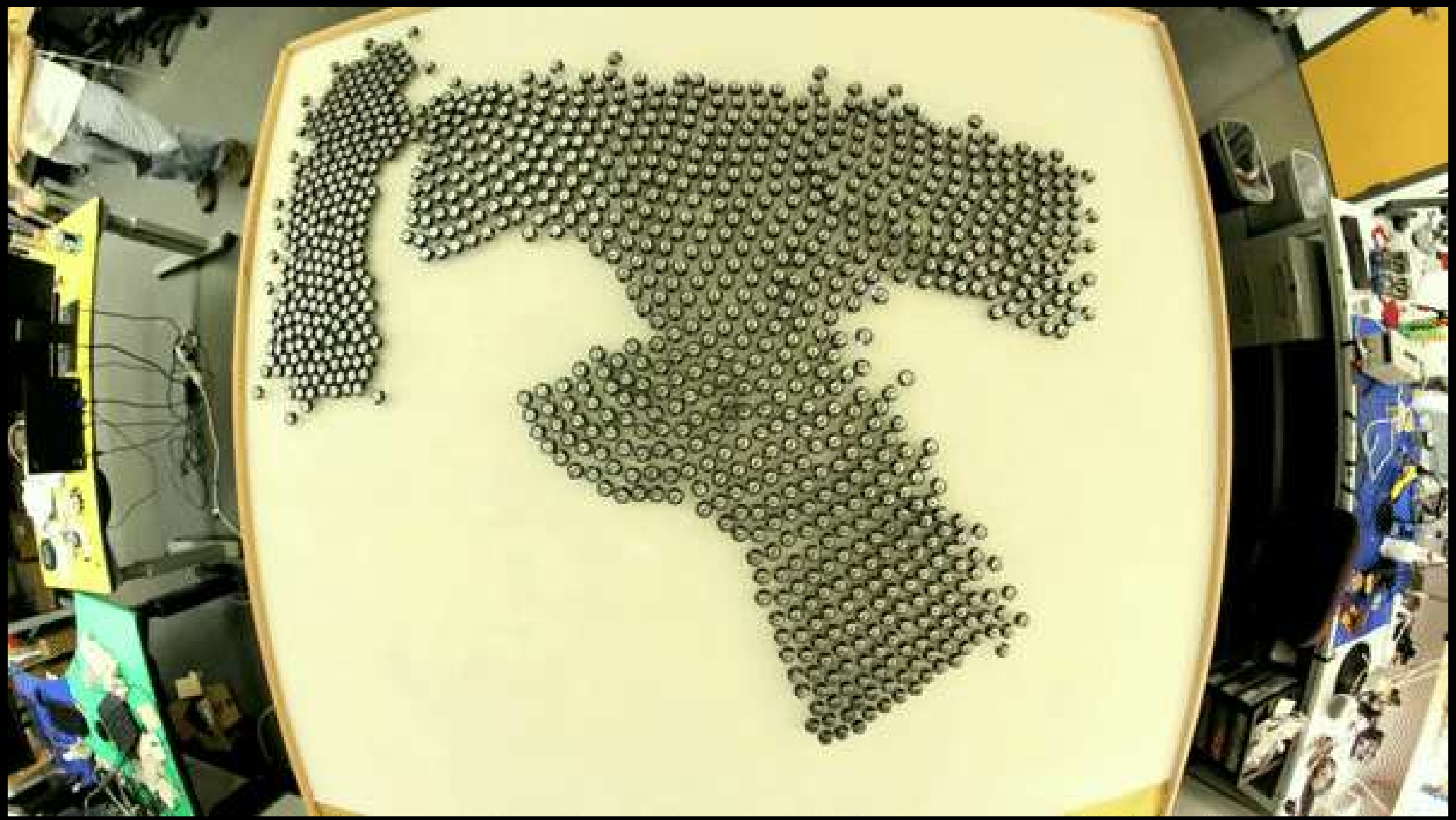
Stakeholder Map

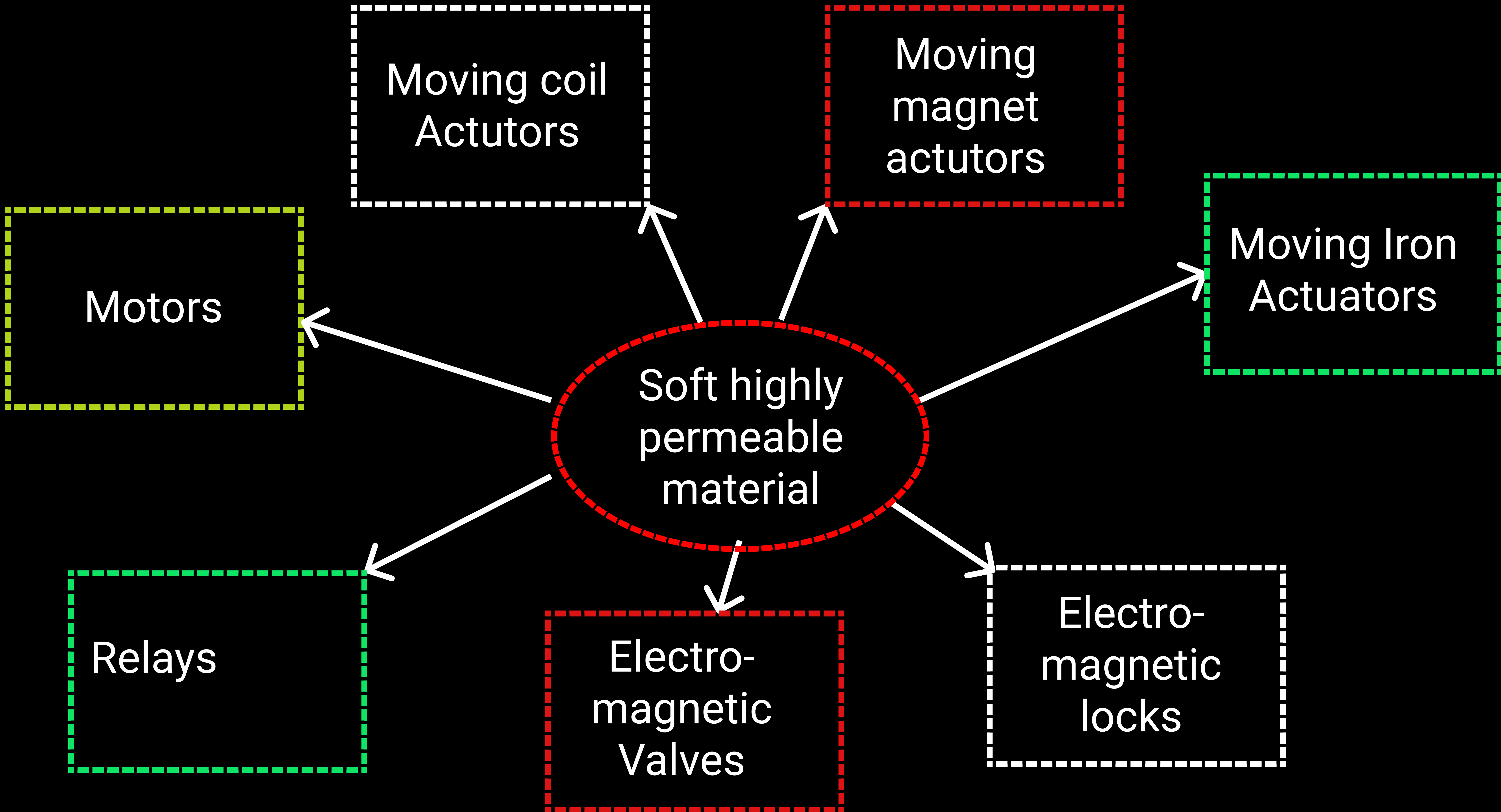




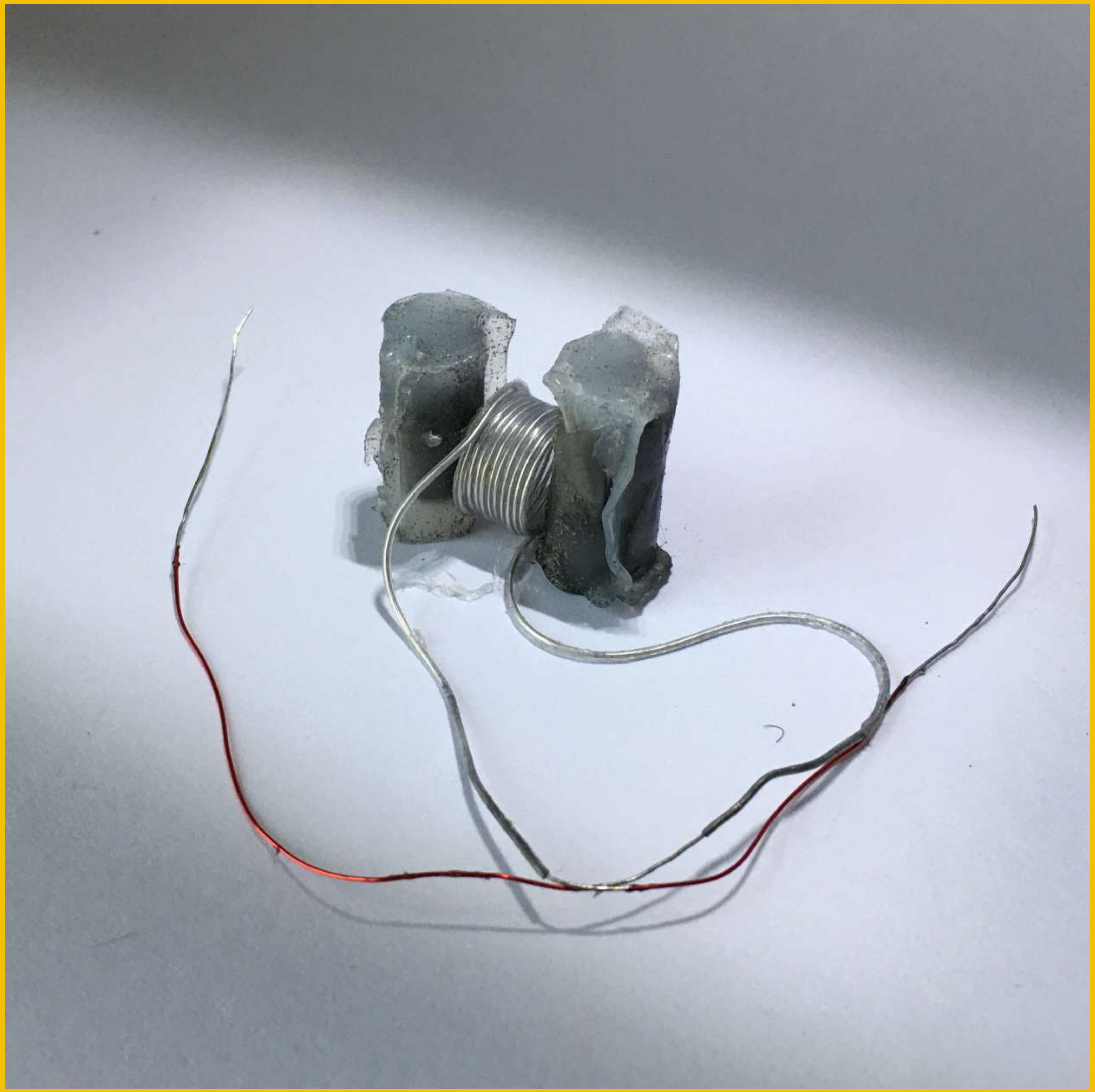


9. Define

Broader System Map

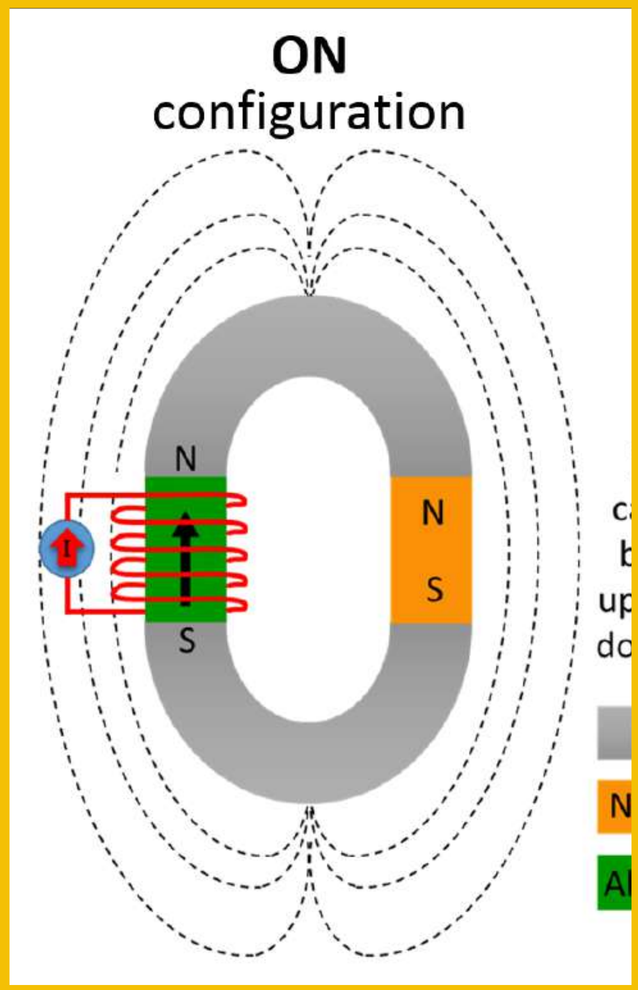


10. Define



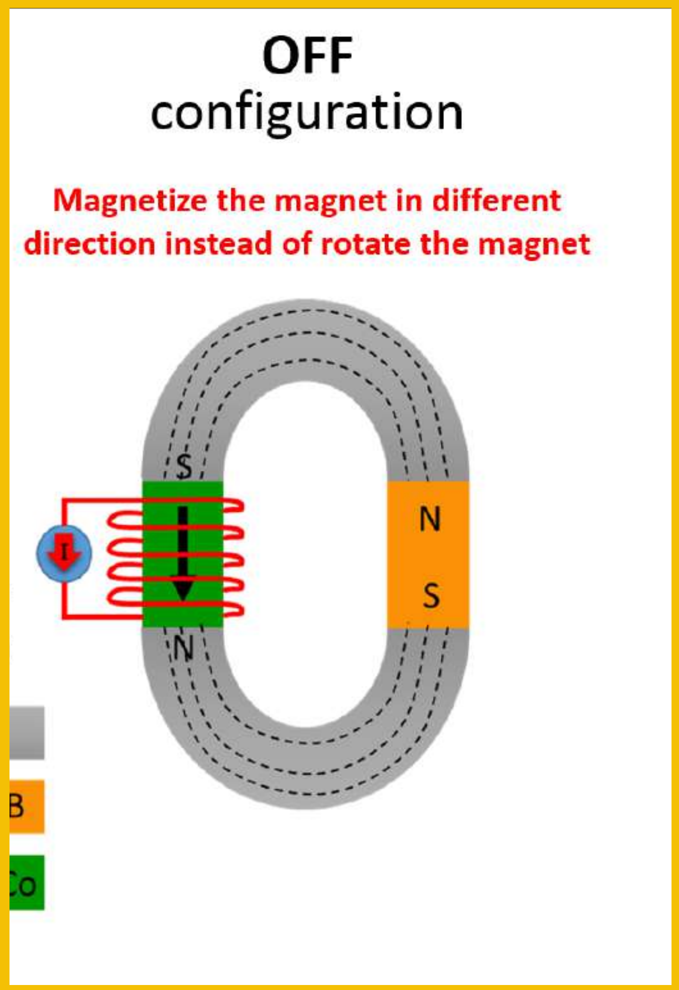
Design

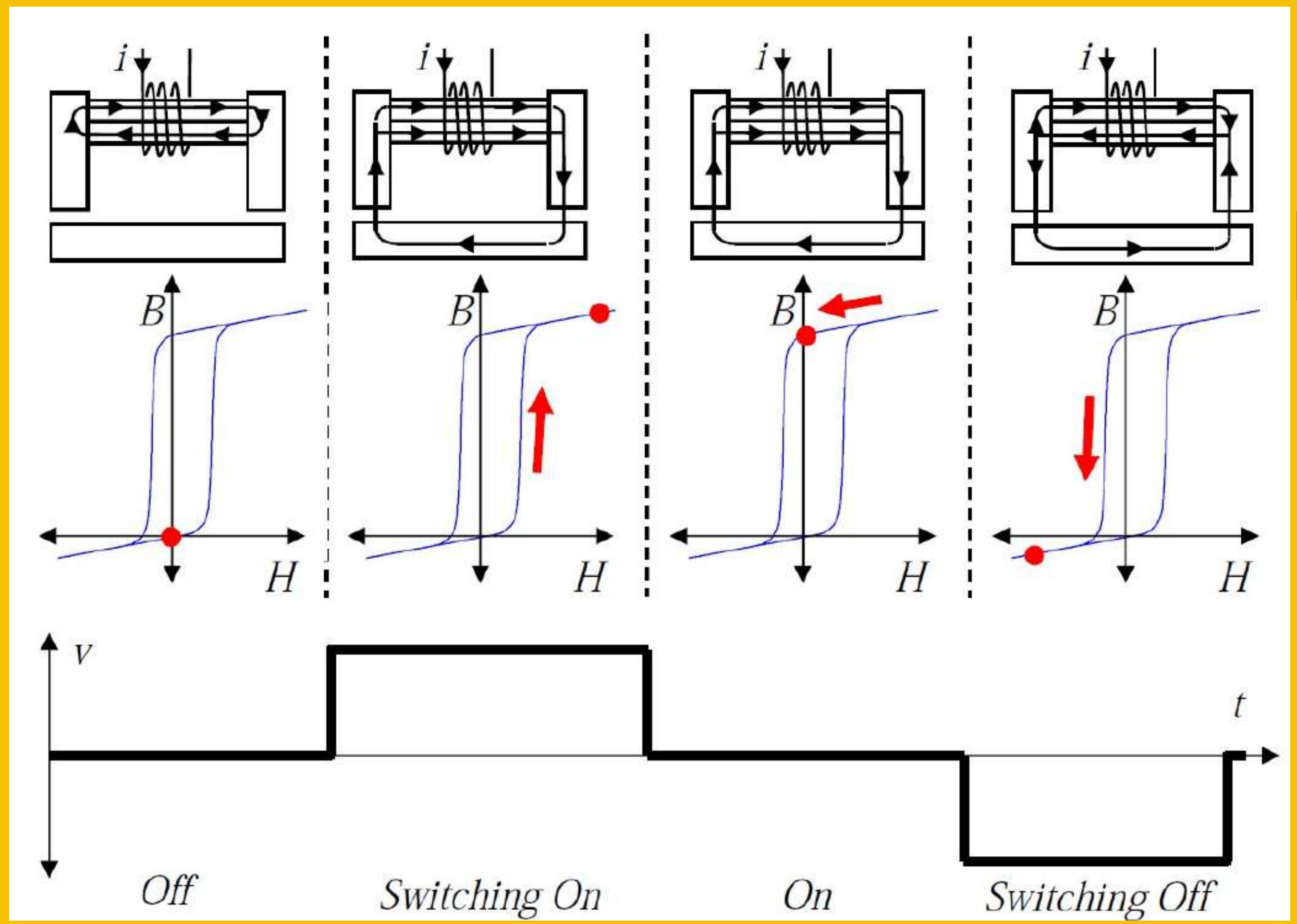
Electropermanent Magnets



[2]

[2]





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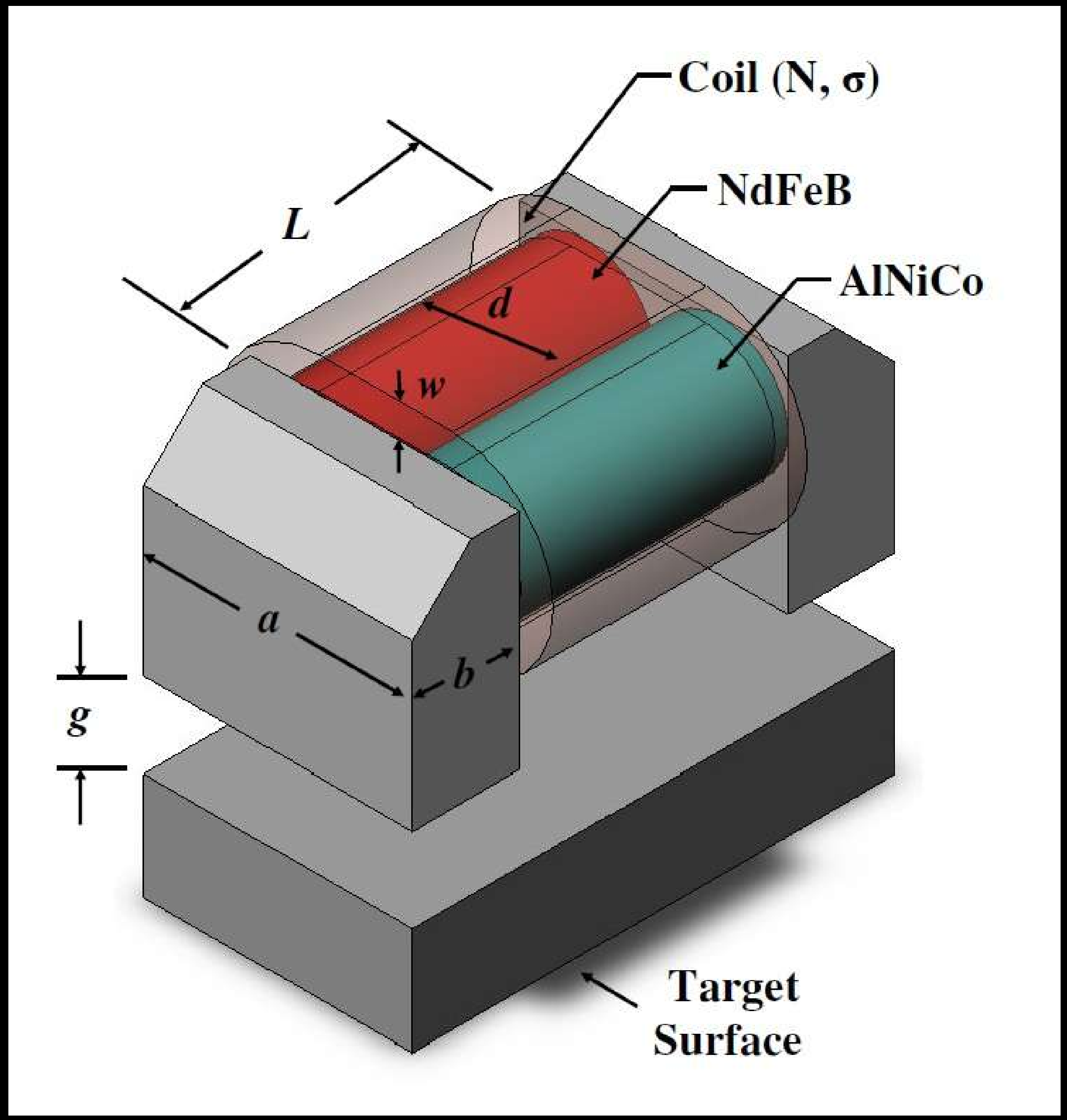
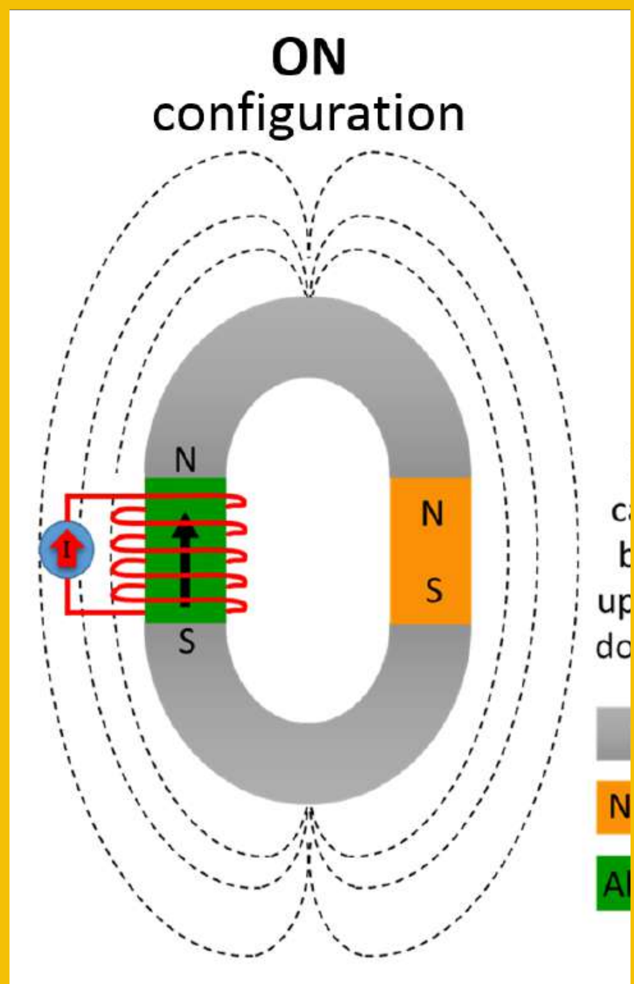


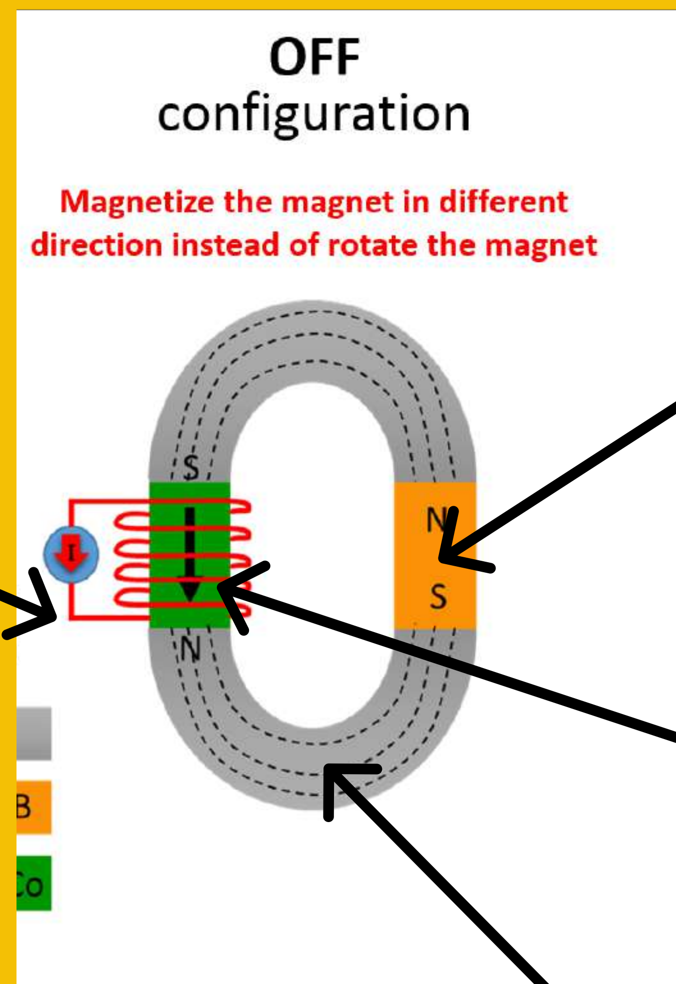
[1]

11. Design

Electropermanent Magnets



[2]



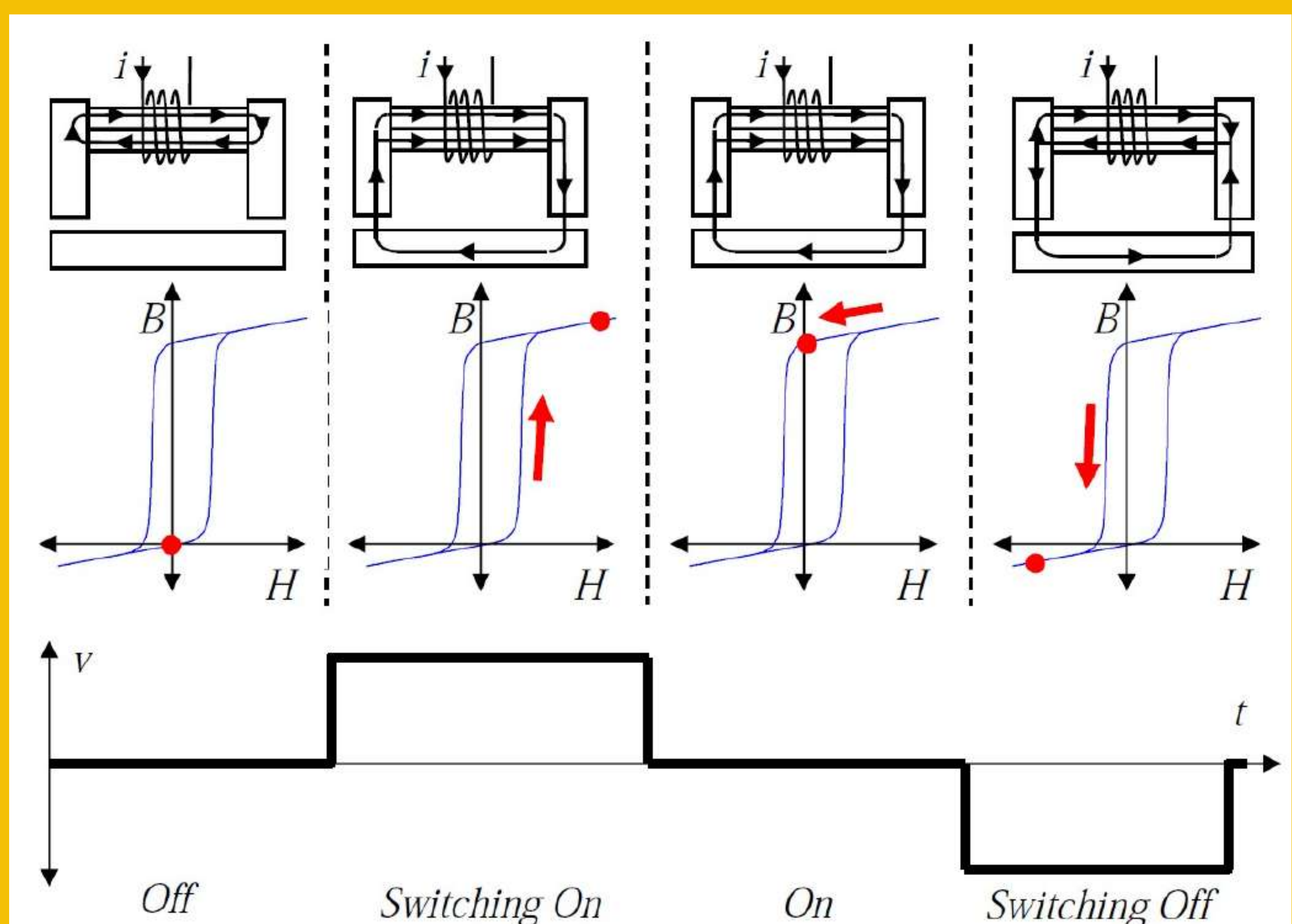
[2]

Coil

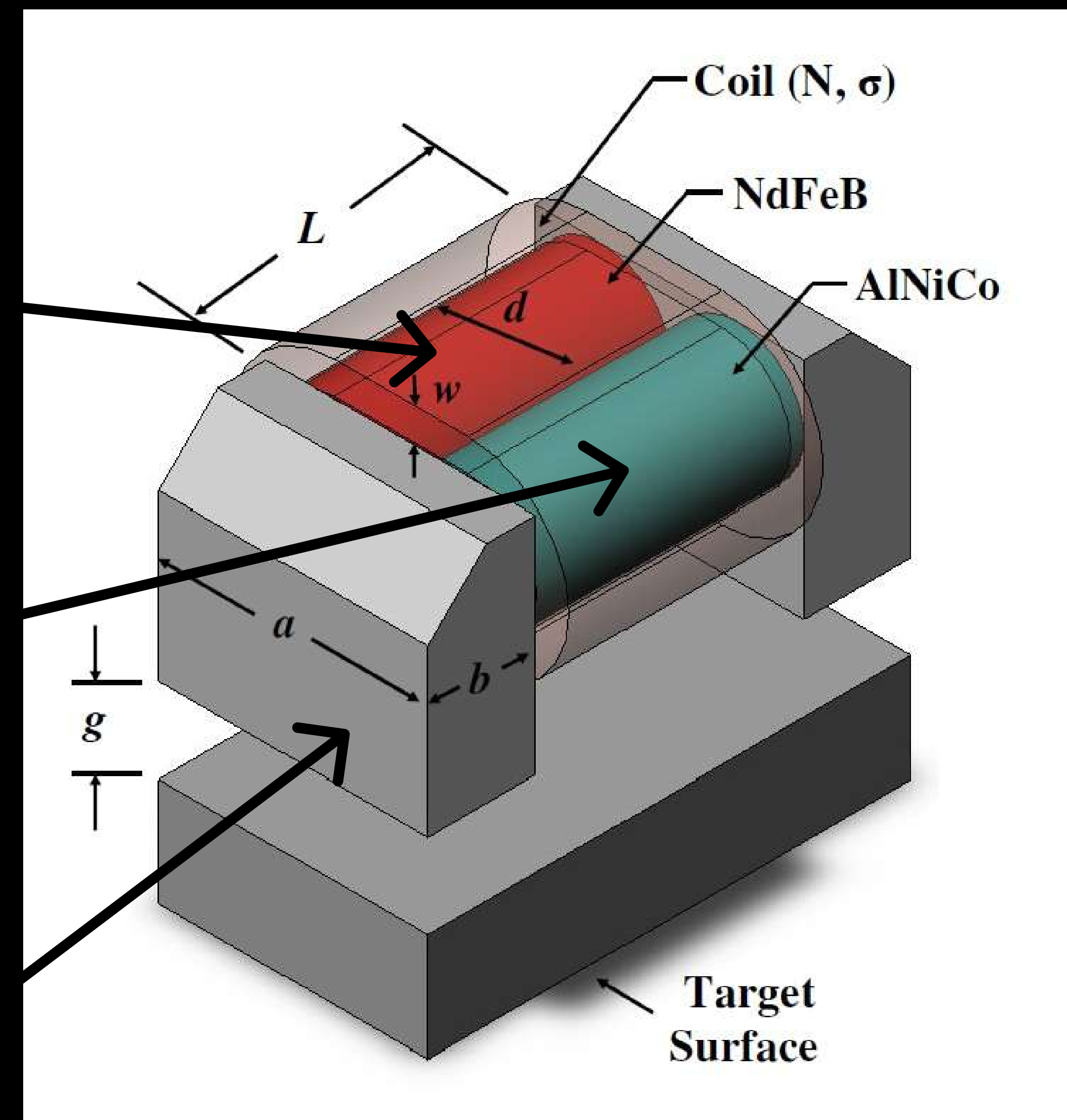
Hard magnet (NdFeB)

semi-hard magnet (AlNiCo)

Iron (Fe)



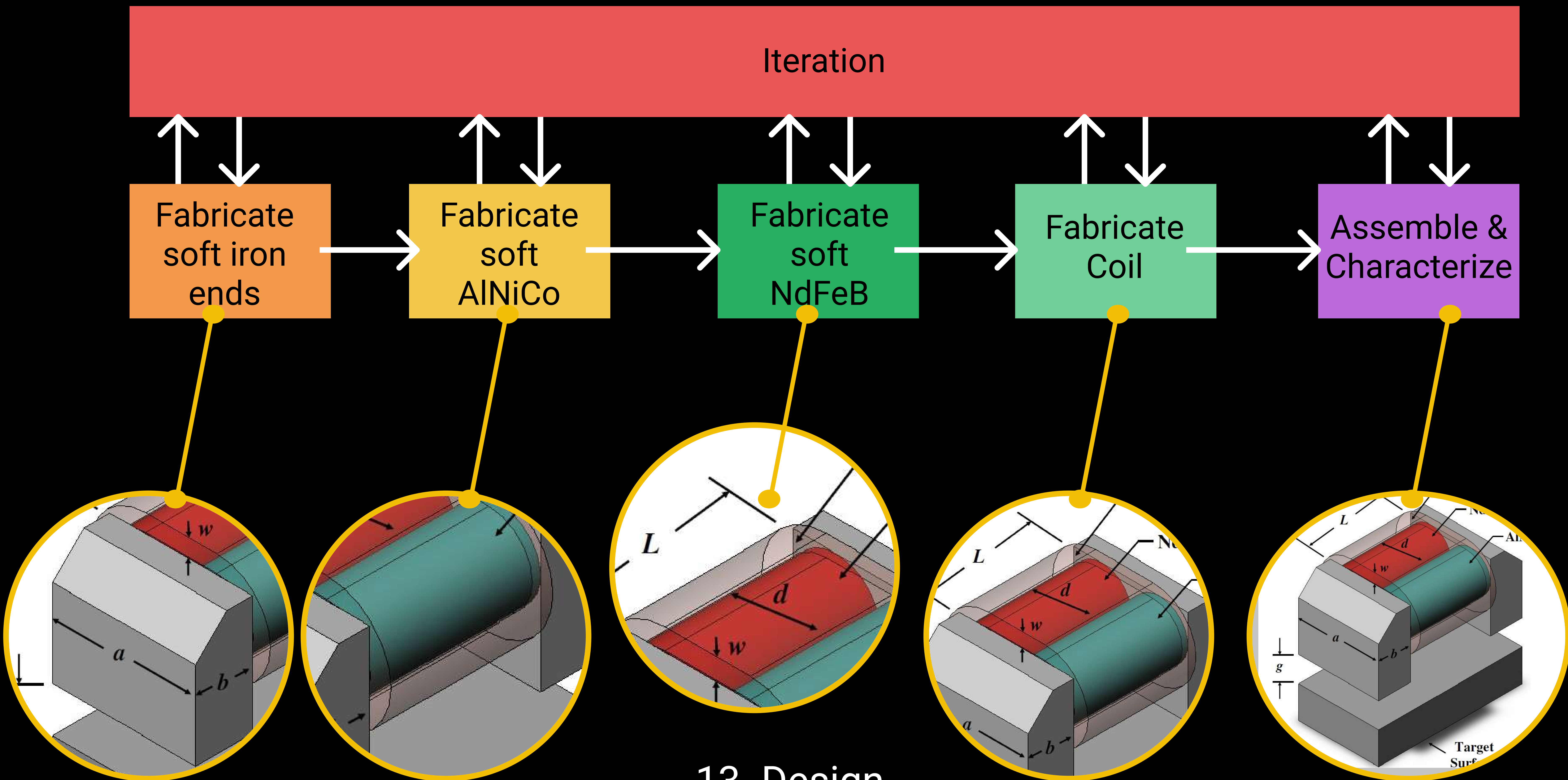
[3]



[1]

12. Design

Project Design Process



Technical Specifications

Specification	***Target value***
Device Scale	1 cm long
Holding Force	20 mN
Soft Iron End relative permeability	10
Compliance	0.001 to 0.05 GPa
Hard Permanent Manget coercivity	1000 kA/m
Semi-hard Permanent coercivity	50 kA/m
Coil conductivity	$3.4 \times 10^6\ Sm^{-1}$.
Coil magnetic field strength	100 kA/m
Coil transient current limit	20 A

Permeability: ability of a material to support magnetic field development

Coercivity: Resistance of a material to be demagnetized

Compliance: Flexibility

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Design Alternatives

Flexible Iron Ends
- Main point of Contact
- Inflexible core

Flexible Iron Ends and Coil
- Still inflexible core

Flexilbe Iron Ends, Core and Coil
- Highest possible compliance
- Material and manufacuring constraints

Soft Iron Ends Design

Permeability-Flexibility Trade-Off

Geometry Design Choices

Flexibility Design Choices

- The volume ratio of iron in the mixture is proportional to the permeability and inversely proportional to the flexibility
- Ecoflex 30

Objective:

Optimize for permeability and the tradeoff is flexibility

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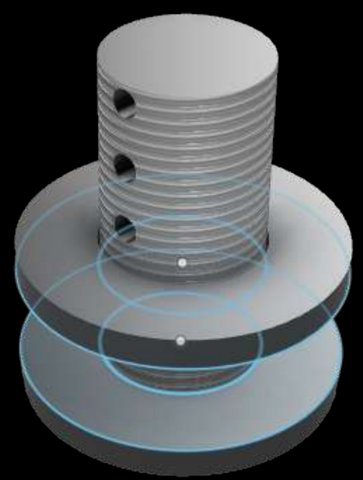
Soft Coil Design

Current-Turns trade off

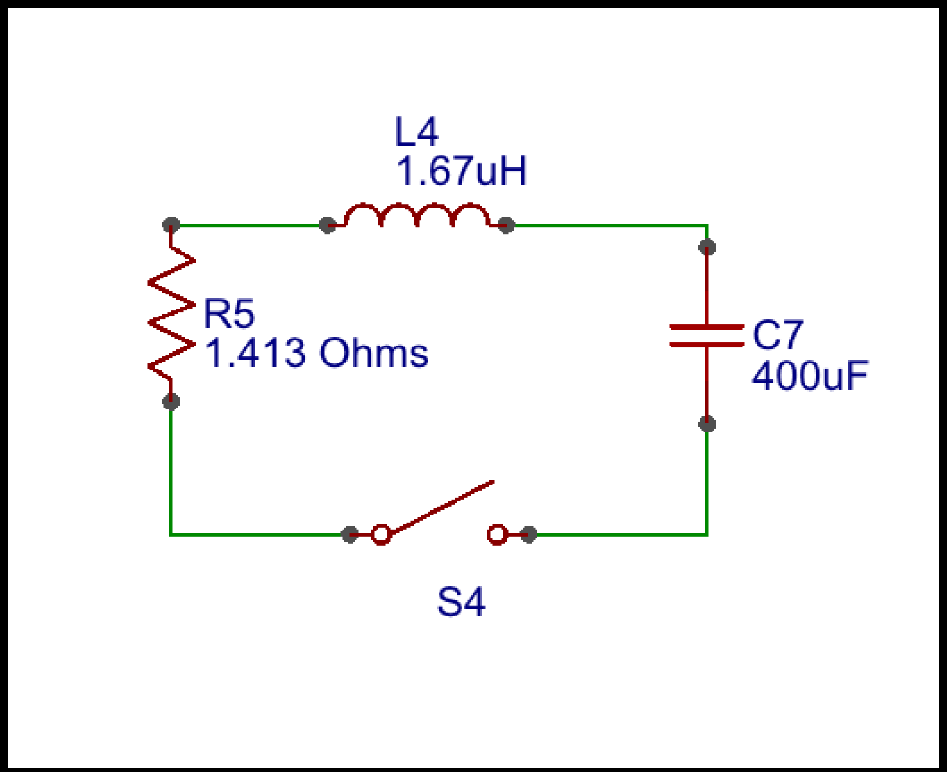
Geometry Design Choices



Flexibility Design Choices

- Silicon tube injected with a conductive liquid metal alloy

Magnetic field strenght



- RLC model with values from prototype

17. Design

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Soft Magnet Design

Force Flexibilty trade off

Geometry Design Choices

Flexibility Design Choices

- The volume ratio of the magnetic particles in the mixture is proportional to the magnetic force and inversely proportional to the flexibility

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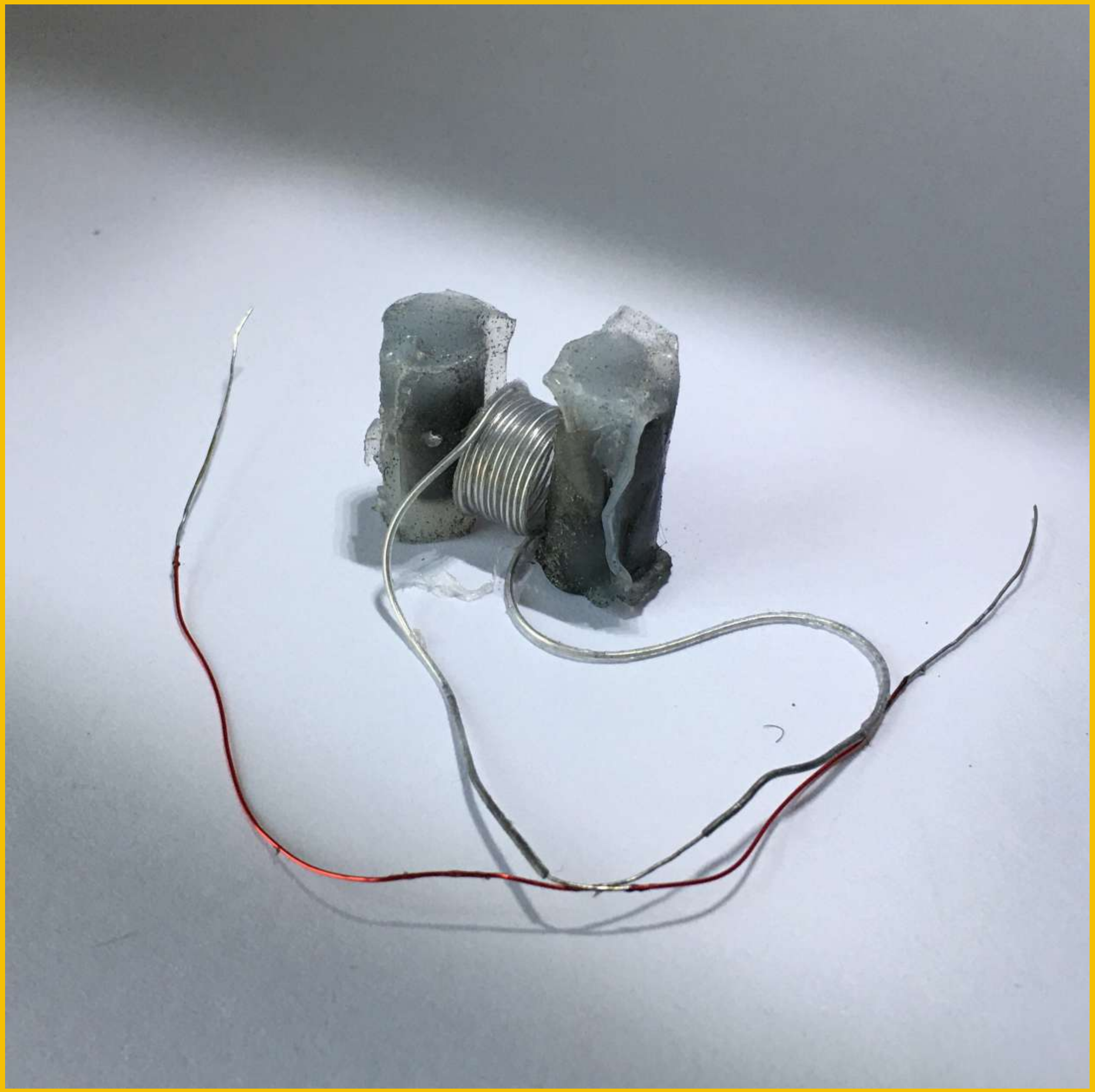
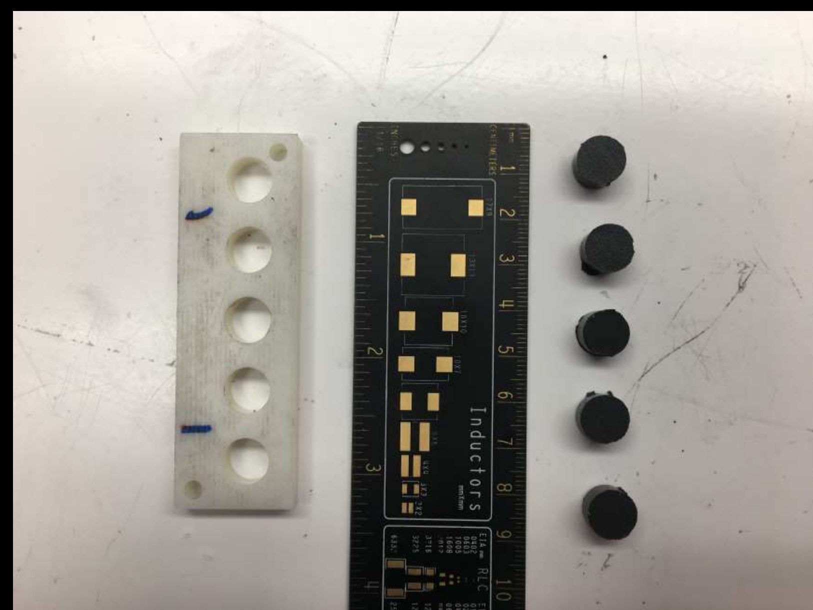


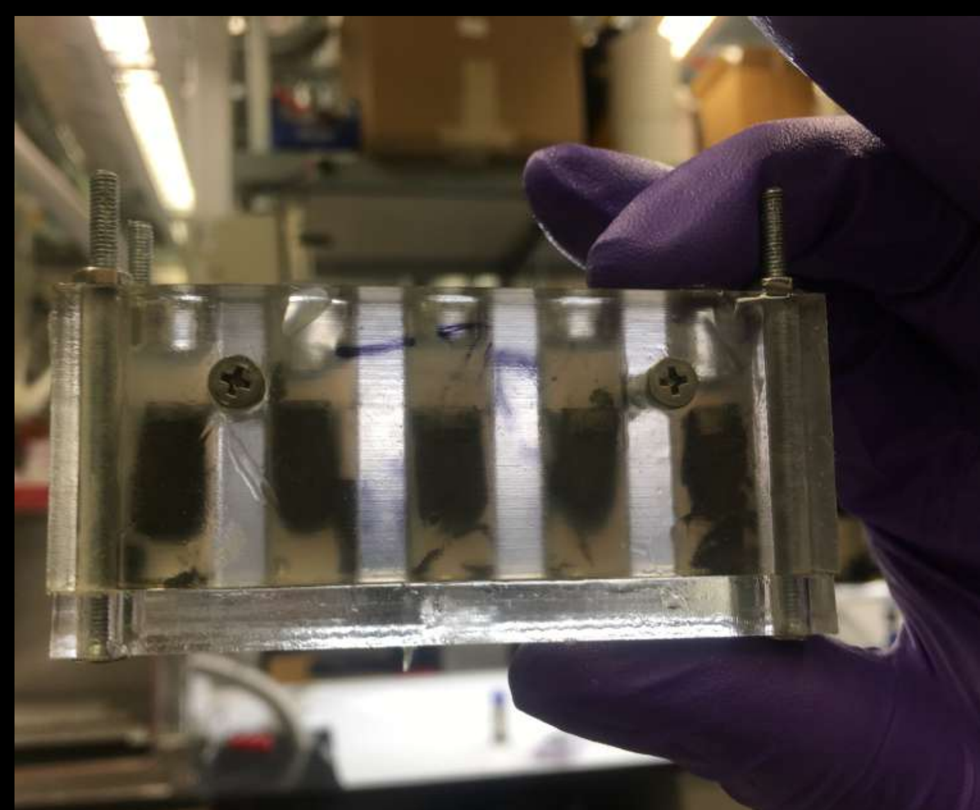
Build

Soft Iron Ends Build

Ferroelastomer (~70 samples)

Particles in a shell


19. Build

Objective:

Optimize for permeability and the tradeoff is flexibility

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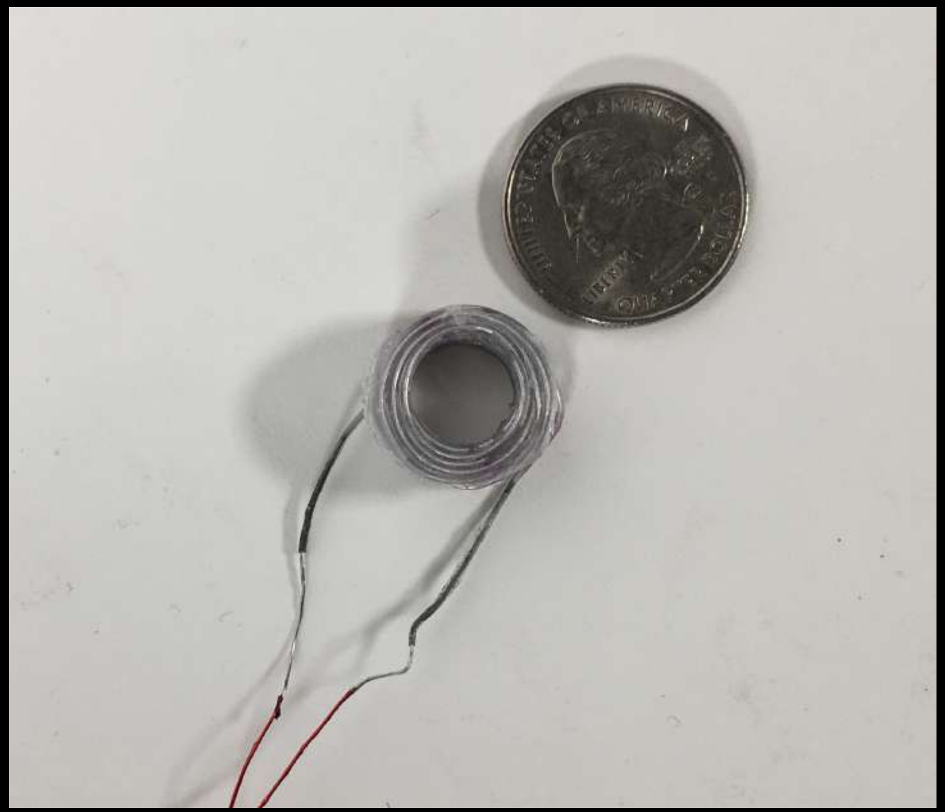
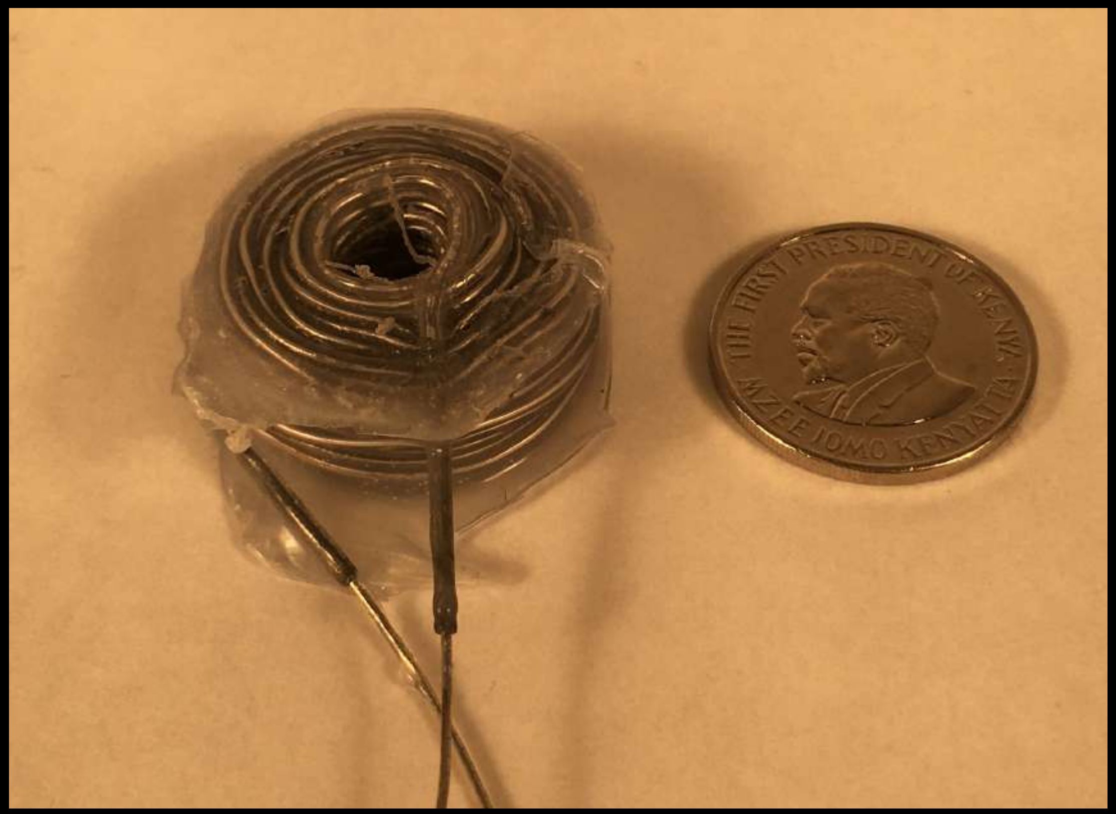
Soft Coil Build

3D printed mold

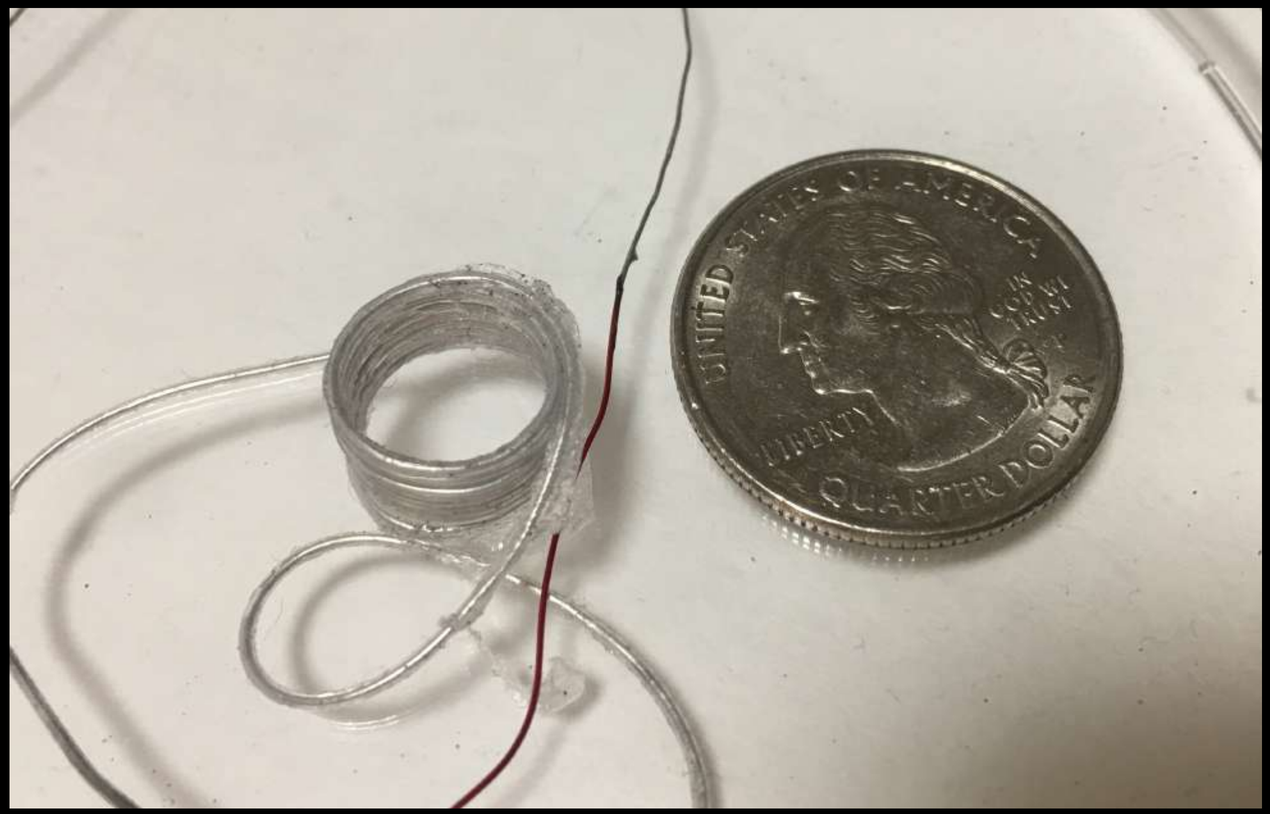
Prototype I



Prototype III



Prototype IV



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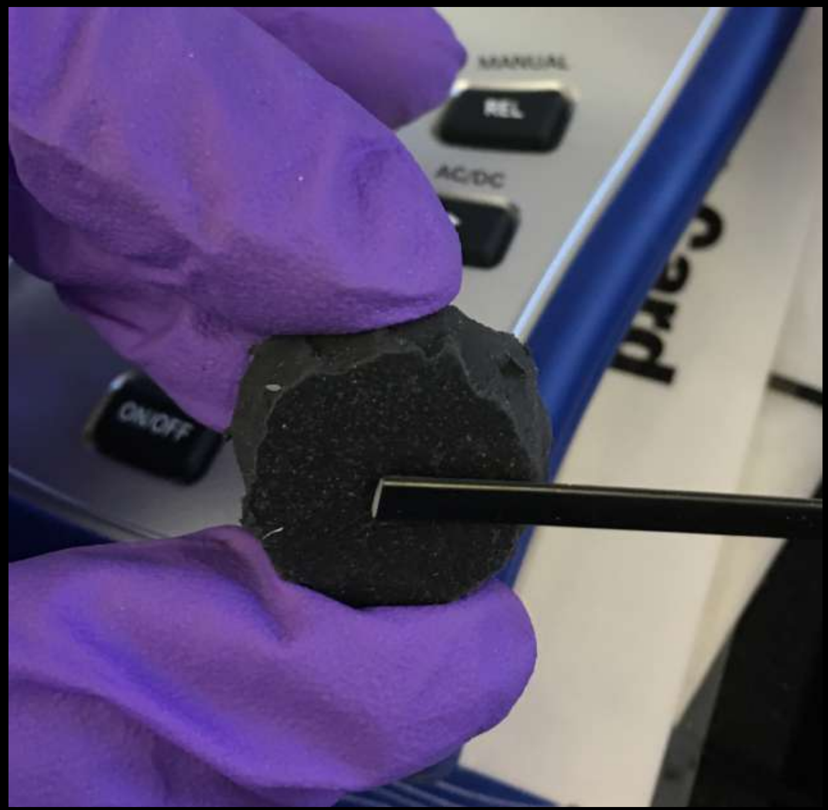
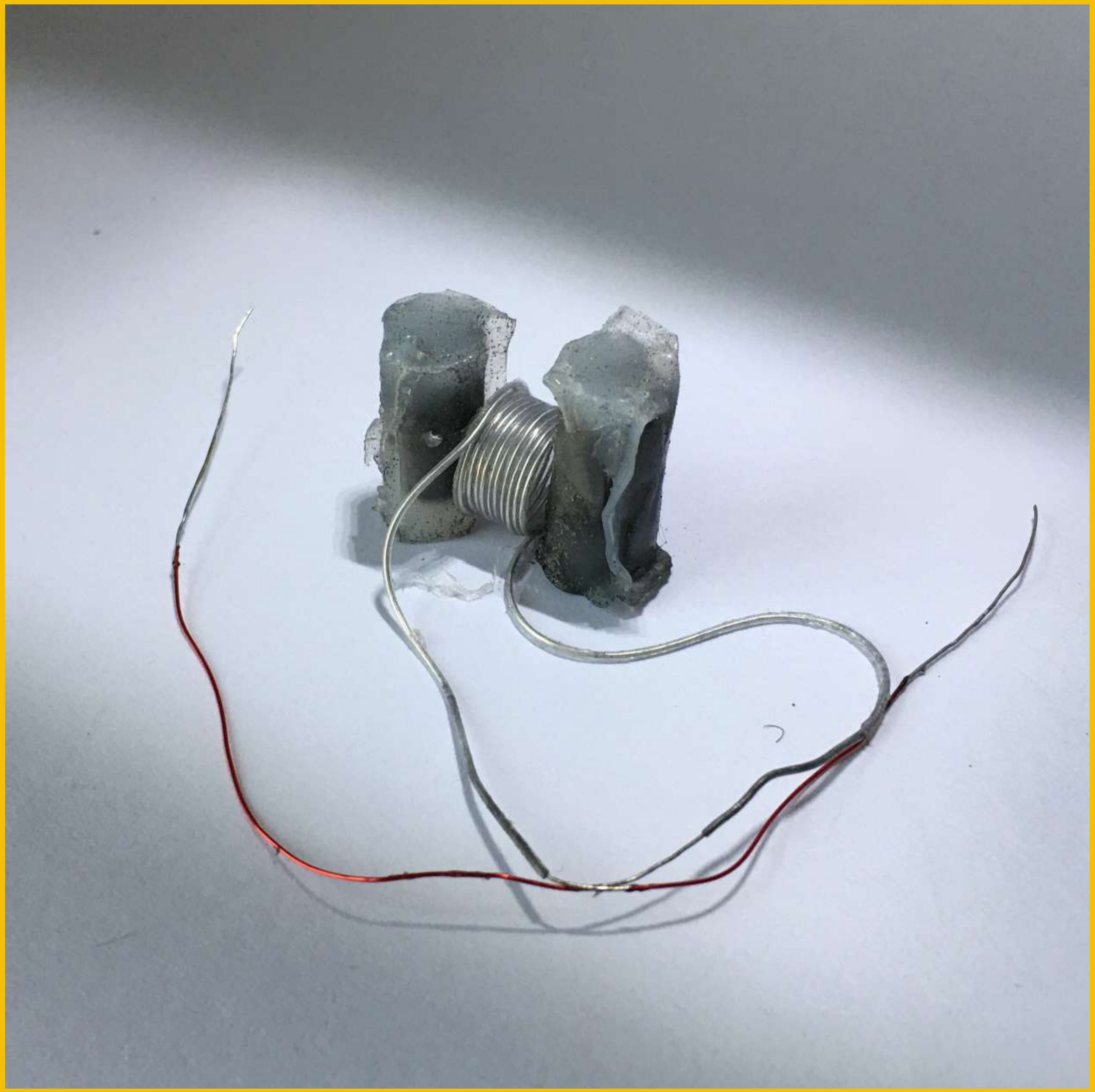
Soft Magnet Build

Hallbach array

Prototype



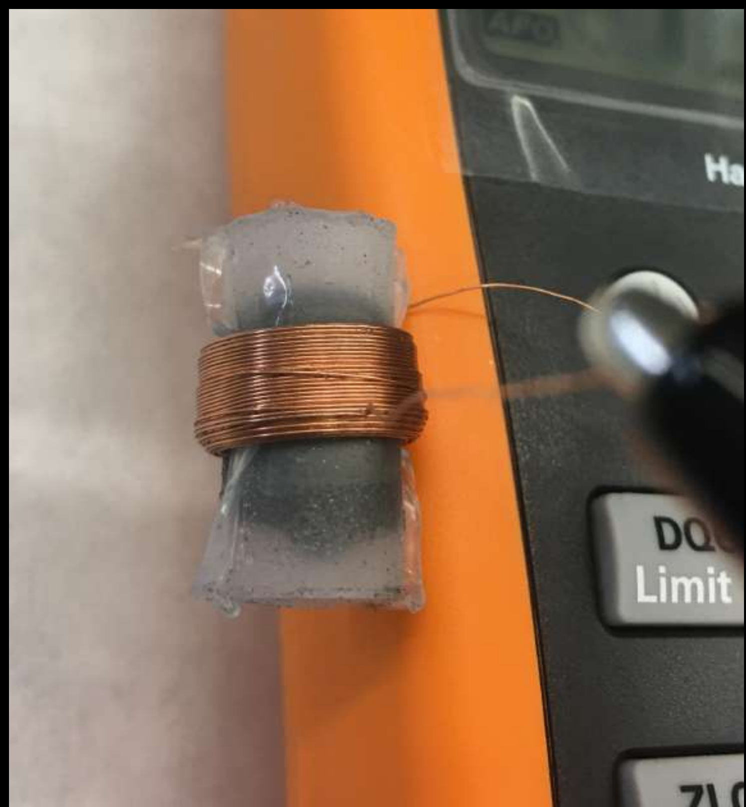
Strontium ferrite is mixed with Ecoflex 30 in the fabrication process



Measure

Measure: Soft Iron ends

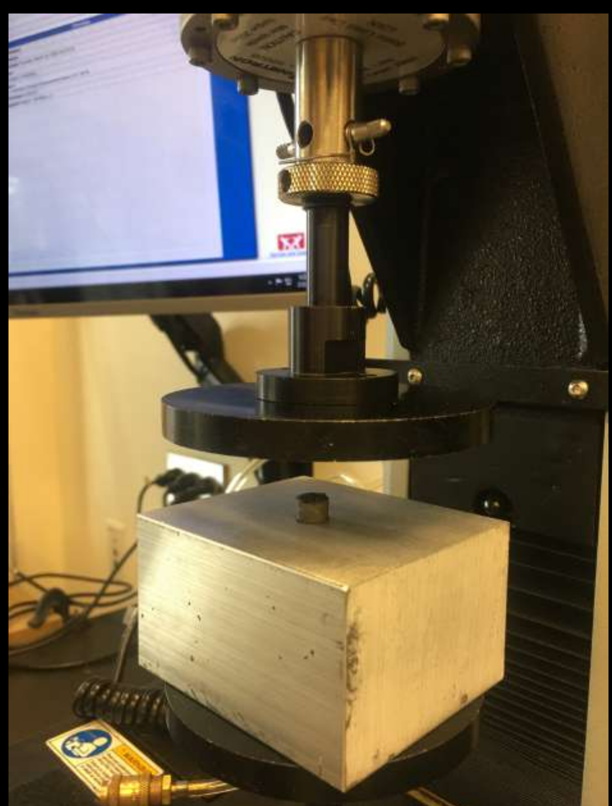
Permeability/Inductance



- RLC Meter
- 200 Turn copper coil

$$L = \frac{\mu N^2 A}{l}$$

Compliance



- INSTRON
- Compression test to determine Young's Modulus

$$E = \frac{F/A}{\Delta L/L}$$

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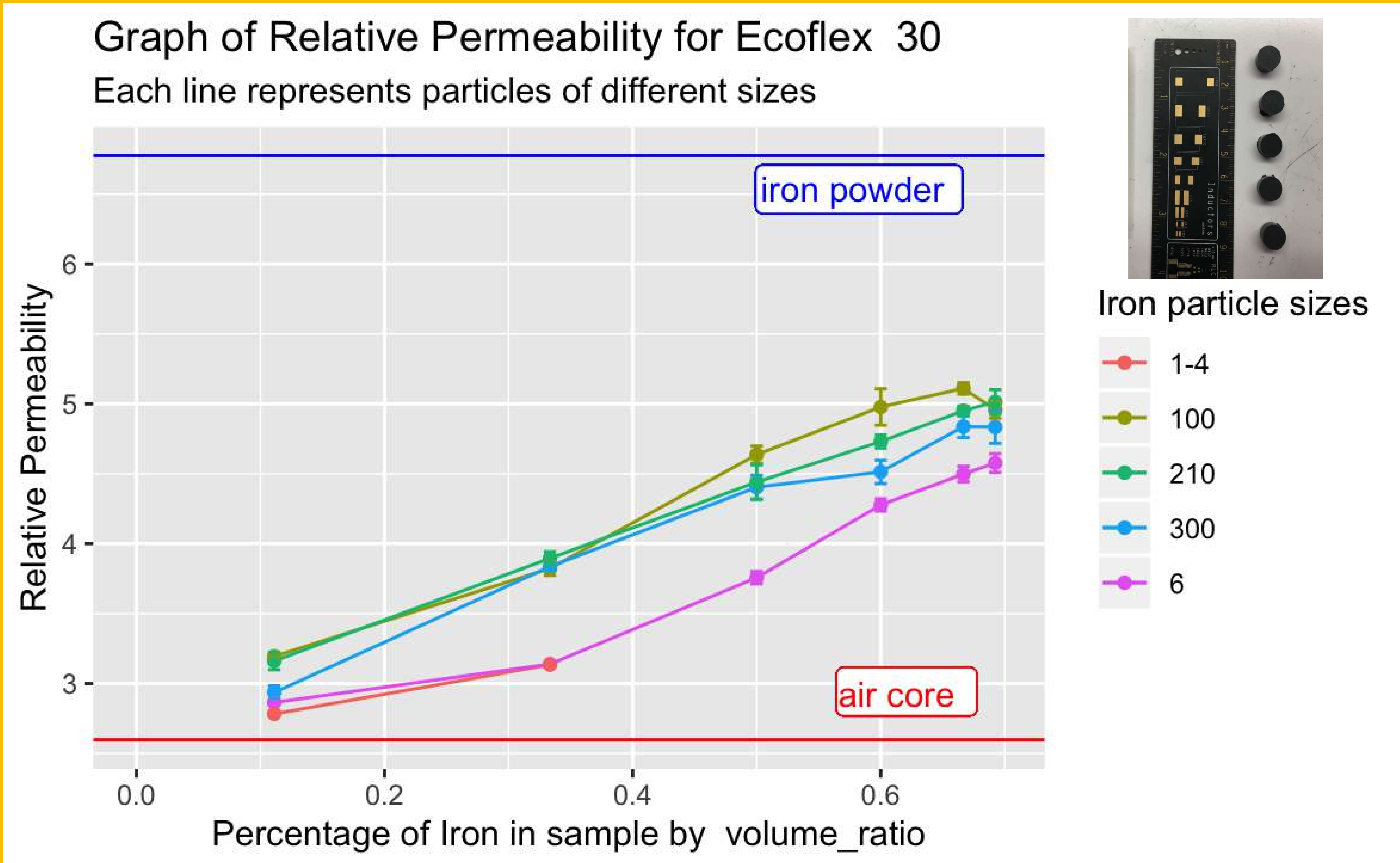
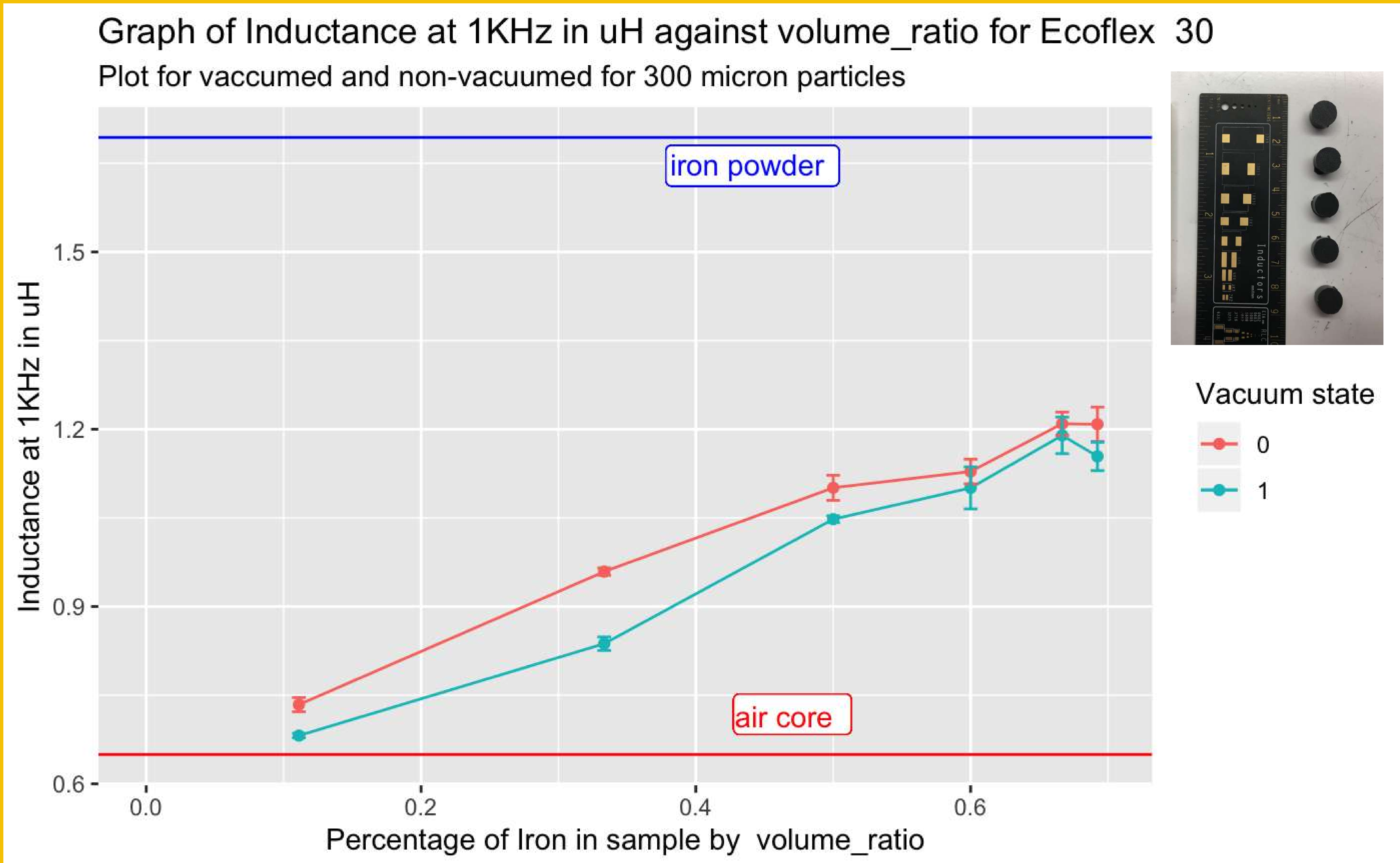
Ferroelastomer Inductance



Vacuumed vs Nonvacuumed ferroelastomer



24. Measure

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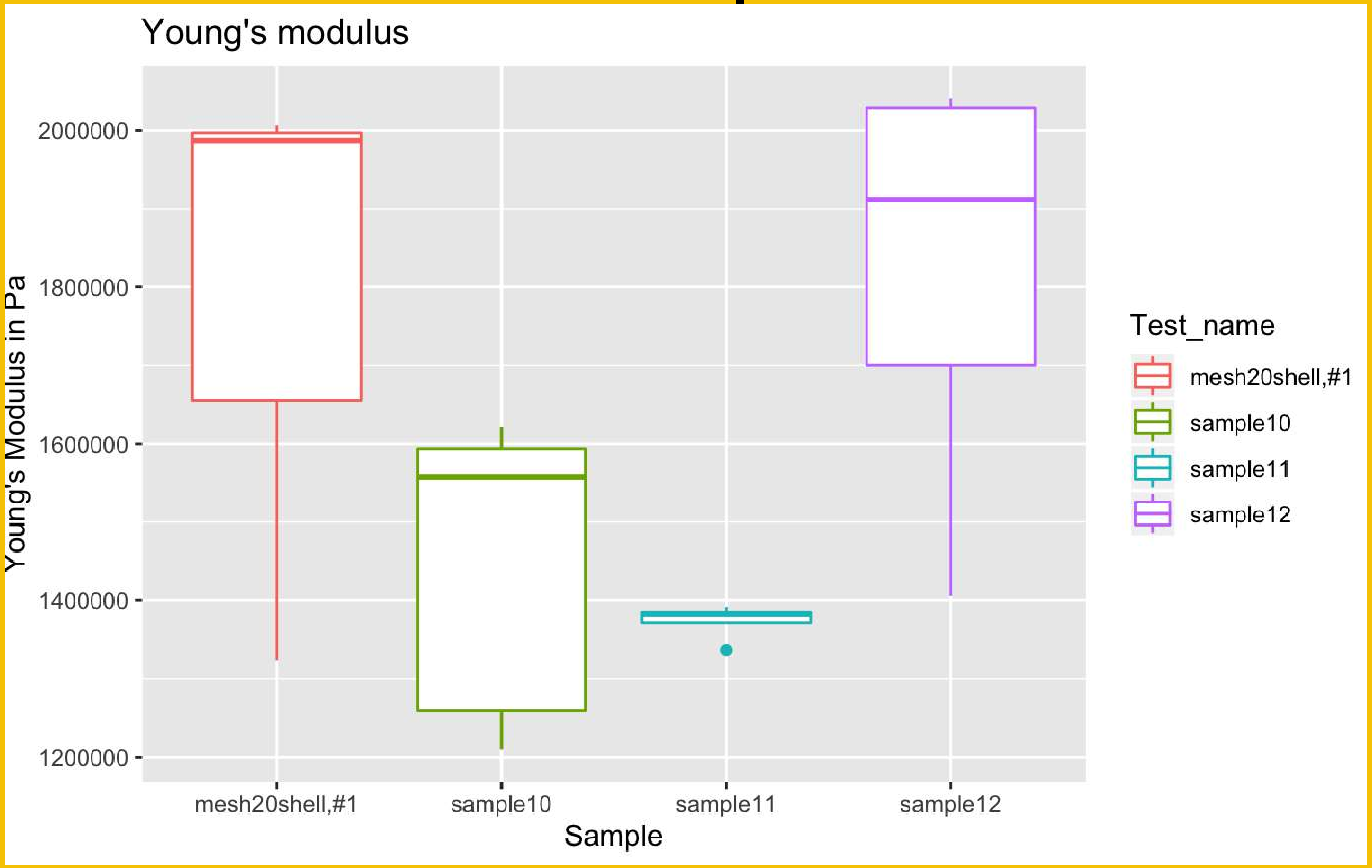
Comparison between ferroelastomer and particles in a shell



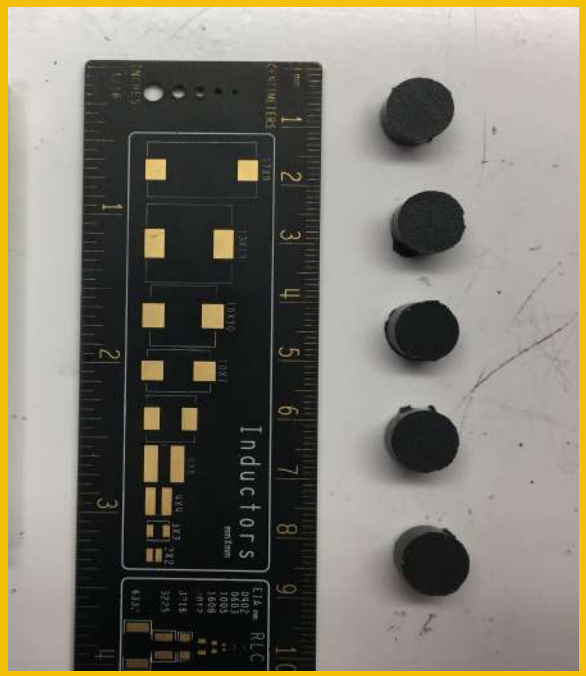


TABLE I. COMPARISON OF INDUCTANCE OF NON-VACUUMED FERROELASTOMER AND NON-VACUUMED PARTICLE IN A SHELL SAMPLE

Sample type	*Particles sizes (microns)*	*Mean Inductance*	*Standard Deviation of Inductance*
Ferroelastomer	100	793.98	17.849
Particles in a shell	100	791.02	18.39

Measure: Soft Coil

Resistance/Resistivity

- Ohmmeter

Inductance

- RLC meter

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Sof Coil Resistivity

TABLE I. SOFT WIRE CHARACTERIZATION

Tube diameter (mm)	*EGaIn Length (m)*	*Electrode diameter*	*Electrode length (m)*	*Total Resistance (Ω)*	*Computed EGaIn resistivity(Ω m)*
0.3	1.20	30 AWG (0.254 mm)	0.11	3.566	2.0791E-7
0.3	1.705	28 AWG (0.32004 mm)	0.14	5.74	2.368E-7
0.5	4	22 AWG (0.64516 mm)	0.073	6.115	2.999E-7

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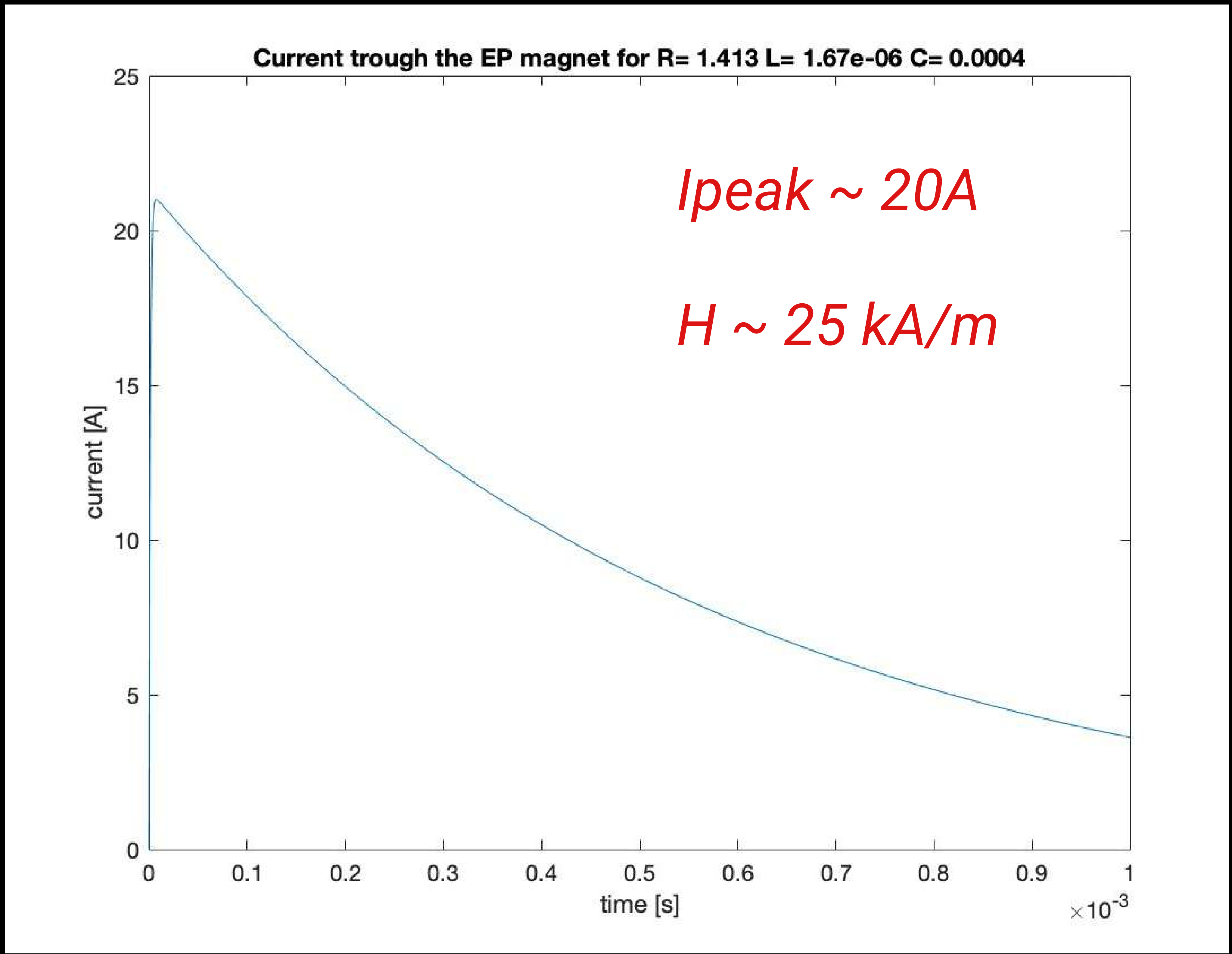
Sof Coil Inductance

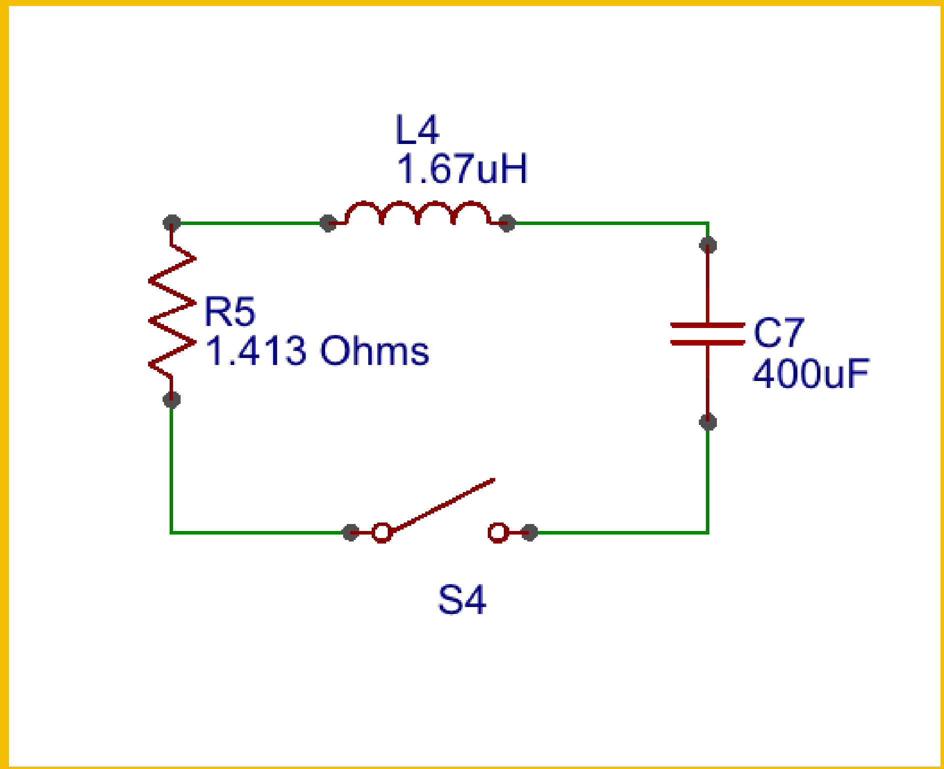
TABLE I. PROTOTYPE IV COIL CHARACTERISTICS

Tube diameter(mm)	*EGaIn Length (m)*	*Electrode diameter*	*Electrode length (m)*	*Total R (Ω)*	*EGaIn resistivity (Ω m)*	*N*	*L uH*
0.3	0.409	28 AWG (0.32004 mm)	0.17	1.413	2.38E-7	10	1.67

Soft Coil Magnetic Field Strength

Overdamped RLC model with R=1.413 Ohms, L = 1.67uH, C = 400uF and l = 8mm





$$H = \frac{N\, I_{circuit}}{\ell_{coil}}$$

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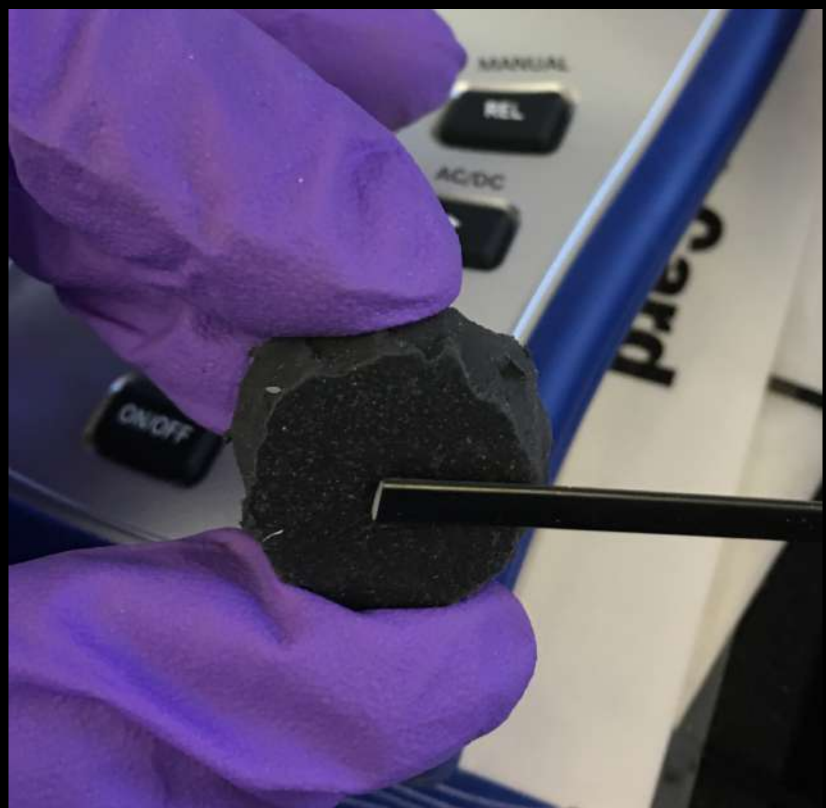
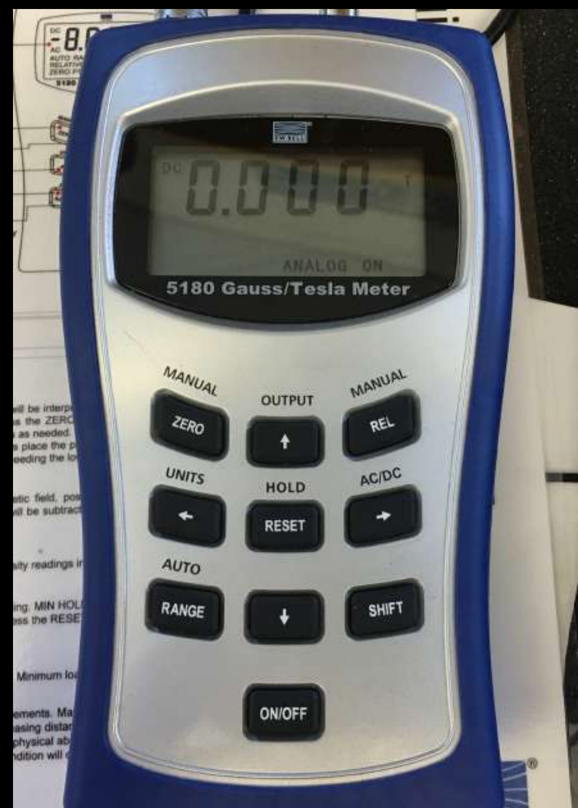
Measure: Soft Perm. Magnet

Remanence





- Gauss meter

Coercivity

- 2.7T Pulse Magnetizer and Gauss meter to create BH graph

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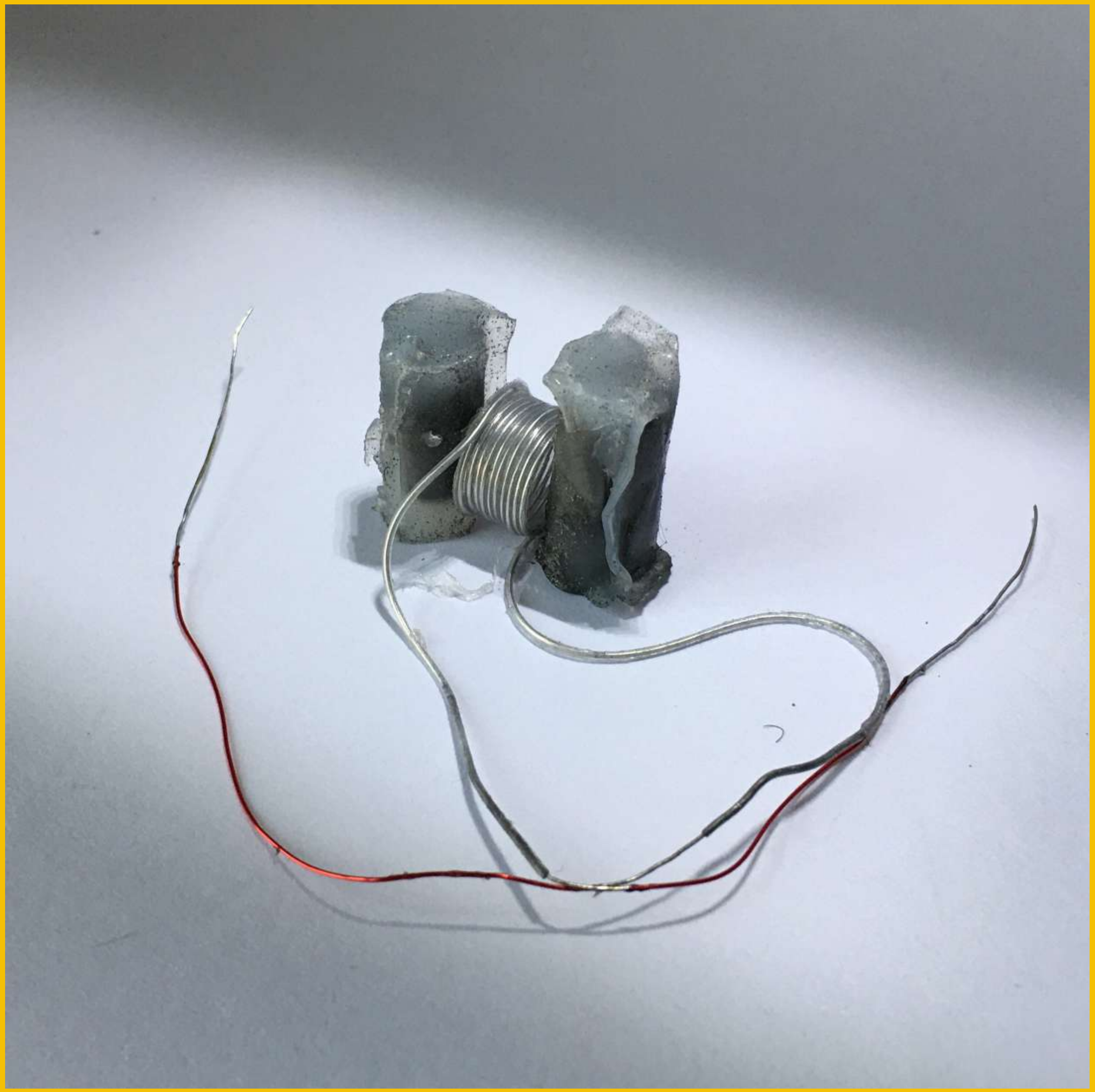
Soft Perm. Magnet Remnance

TABLE I. STRONTIUM FERRITE MAGNETIC CHARACTERISTICS

Sample #	*Mass ratio of SrFe*	*Smooth side [T]*	*Rough side [T]*	*Edge B [T]*
1	0.8	0.015	0.006	0.02 6
2	0.7	0.015	0.006	0.01 4

TABLE I. MAGNETIC PARTICLES GRADES[13]

Material	*Grade*	*Coercivity (kA/m)*	*Remanence Br (T)*
NdFeB	N40	1000	1.28
AlNico	LNG40	50	1.26



Conclusion

Achieved Tech Specs

Specification	*Target value*	*Achieved value*
Device Scale	1 cm long	2.7 cm
Holding Force	20 mN	-
Soft Iron End relative permeability	10	5.2
Compliance	0.001 to 0.05 GPa	0.001 to 0.002 GPa
Hard Permanent Manget coercivity	1000 kA/m	-
Semi-hard Permanent coercivity	50 kA/m	-
Coil conductivity	$3.4 \times 10^6\ Sm^{-1}$.	$4.03 \times 10^6\ Sm^{-1}$
Coil magnetic field strength	100 kA/m	25 kA/m
Coil transient current limit	20 A	-

Permeability: ability of a material to support magnetic field development

Coercivity: Resistance of a material to be demagnetized

Compliance: Flexibility

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Future Work and Potential Impact

- Force Characterization
- Size optimization: E ~ V, F ~ A
- Soft Permanent Magnet Fabrication
- Soft Coil Optimization H = (N i) / l
- Composite material characterization is of use to those designing soft magnetic devices eg soft motors, soft relays, soft moving iron actuator, soft electromagnetic valves

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Acknowledgement

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- Active Learning Labs Staff
- ES100 Staff
- ES 100 peer support group

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Thank

You!

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