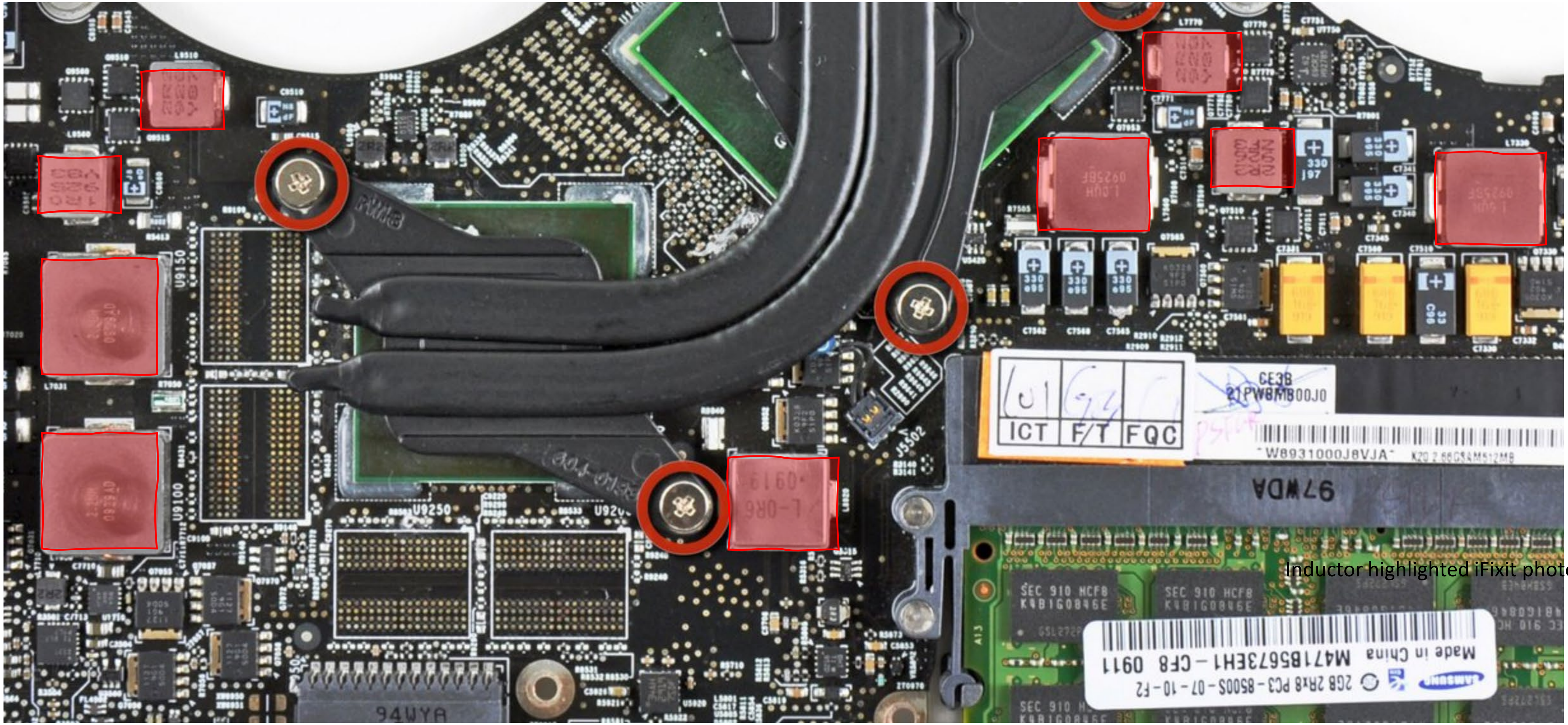
ATLAS MAGNETICS

APEC – Thin Film Magnetics

Quick Background

Red tint are inductors that could be integrated



Inductor highlighted iFixit photo

Thin Film Magnetics Promise

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- Lithography enables coupled inductors, transformers, multi-tapped inductors, and toroids at the same cost structure
- Thin films achieve higher operating frequency, > 100 MHz
- Lot Processing greatly improves inductor to inductor matching for multi-phase applications
- Closer proximity to load reduces I^2R losses
- High Bsat materials allow thinner solutions

Thin Film Magnetics Problems

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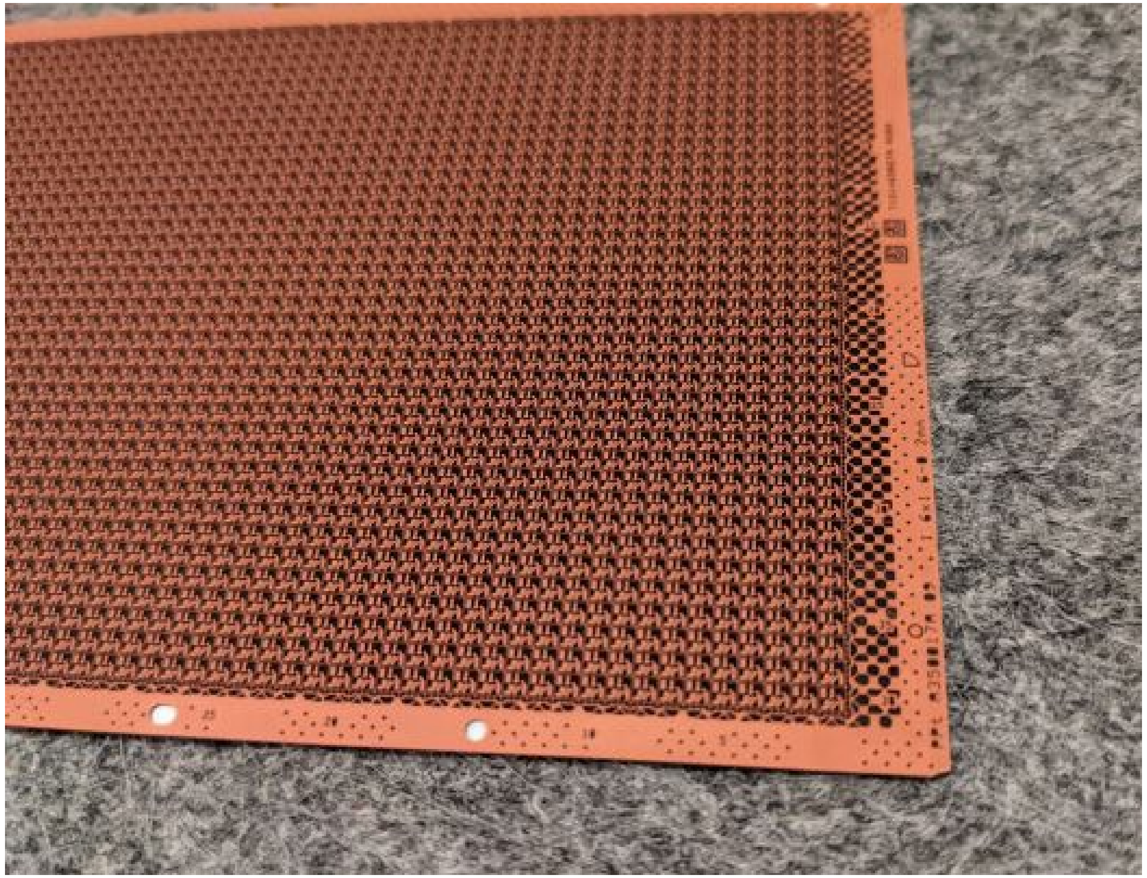
- Wafer deposition causes warping which limits magnetics thickness – AM found significant warping at >12um.
    - Less magnetics = lower inductance = high switching frequency = less voltage drop
- Thin film materials have low resistance but high eddy current losses. Thinner materials cause either 1) lower inductance or 2) extra layering which multiplies cost
- “Fixing” the resistance problem increases domain wall pinning, often dramatically increasing coercivity (1→50 Oe). AM has mitigated this issue, but no metamaterial has better coercivity than its most similar alloy
- Magnetic thin films are often unstable in permeability and Q over temperature. AM had variability challenges [+15%, -70%] adding over a year to development. Thin film permeability changes are not consistent with alloy % differences or additives. Sufficient stability is required in electronics to endure 260°C reflow and life testing.
- Electroplating requires a parasitic seed layer which damages performance over frequency < 5 MHz
- Wafer-level research is often slow, very expensive, and can be geometry-dependent.
    - A 10-layer magnetic stack requires 10 resist layers, 10 anneal, 10 deposition, cleaning, prep, etc. Months of work!

Millions of Magnetics in a Standard IC Substrate

Scalable to massive volume with widely available production equipment

Material with known MSL ratings and processing methods



Similar cost structure to discrete inductors

Size Comparison

Today

Original, all external passives

Retrofit

Existing 1A DC/DC AP61102 w/ integrated inductor in 1.8x1.8 mm package

With AM Silicon

AM32101: 1A DC/DC w/ integrated inductor in 1.6 x 1.6mm package, programmed w/o external resistors

Example of AM Inductor Built with Advanced Packaging

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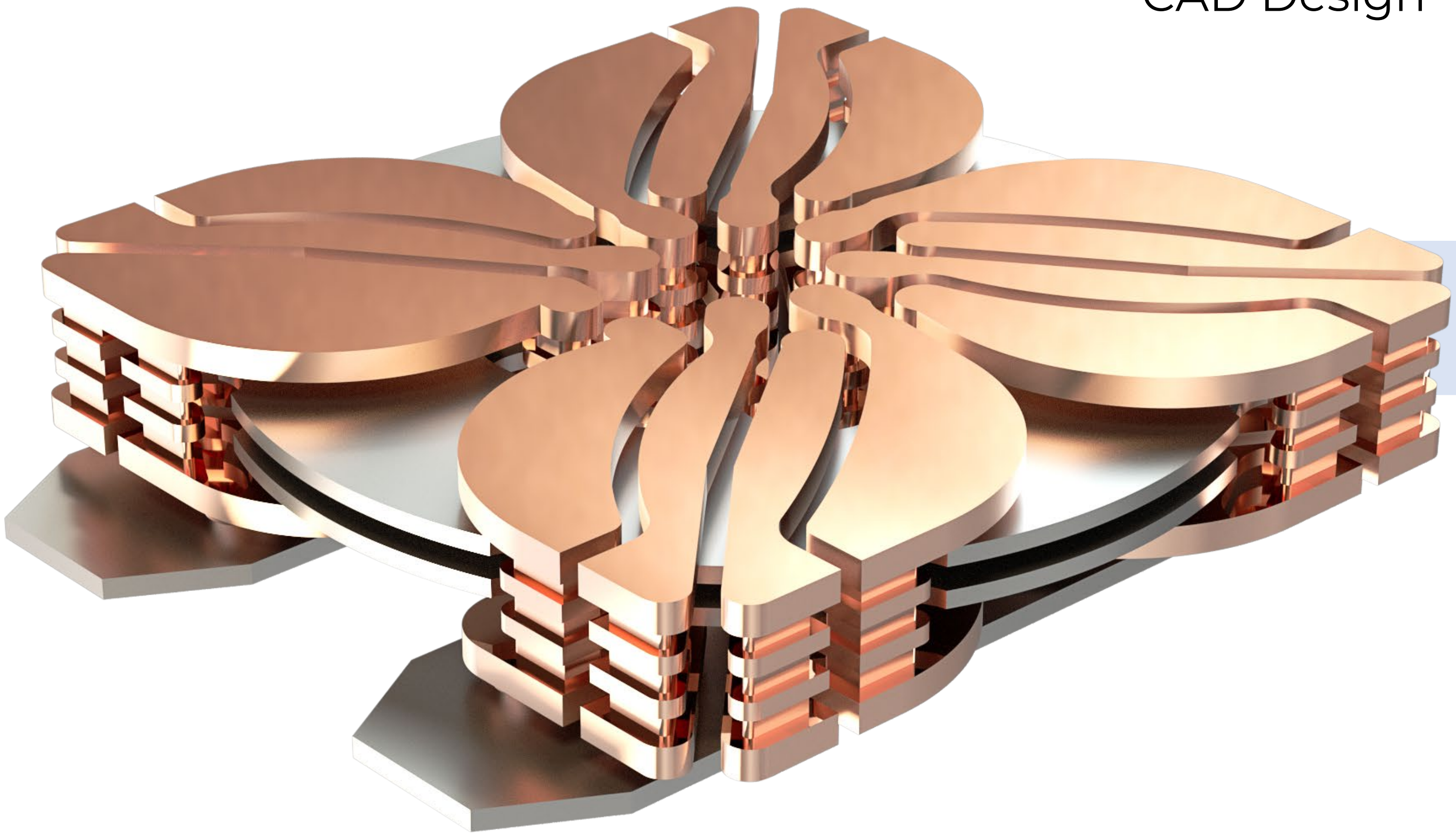
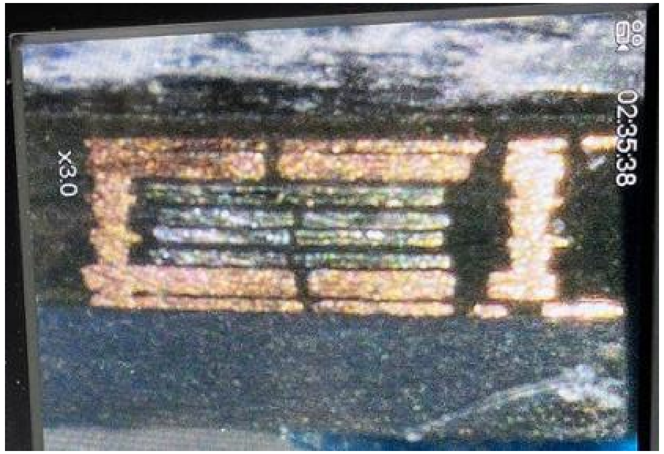
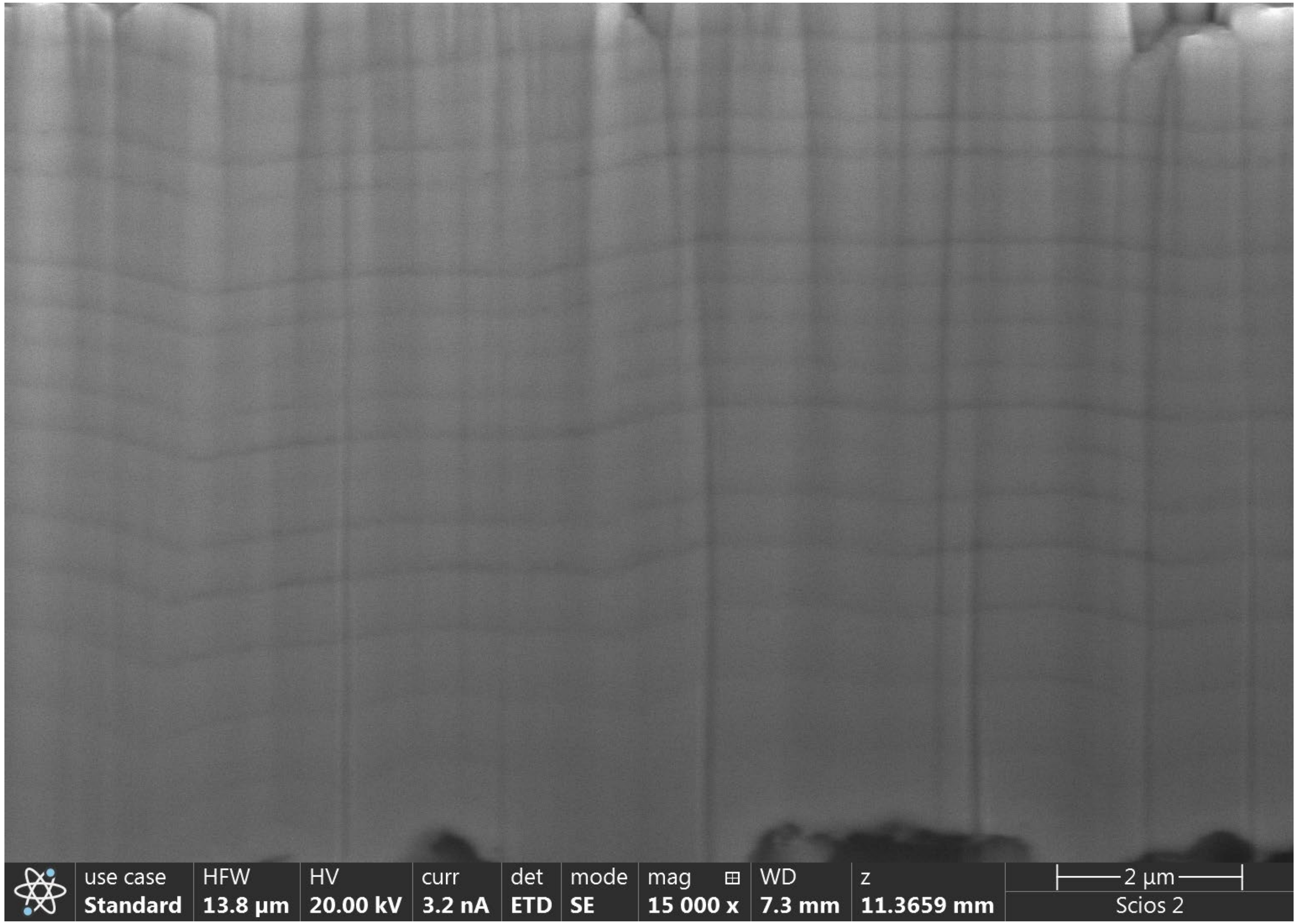
CAD Design



Reality



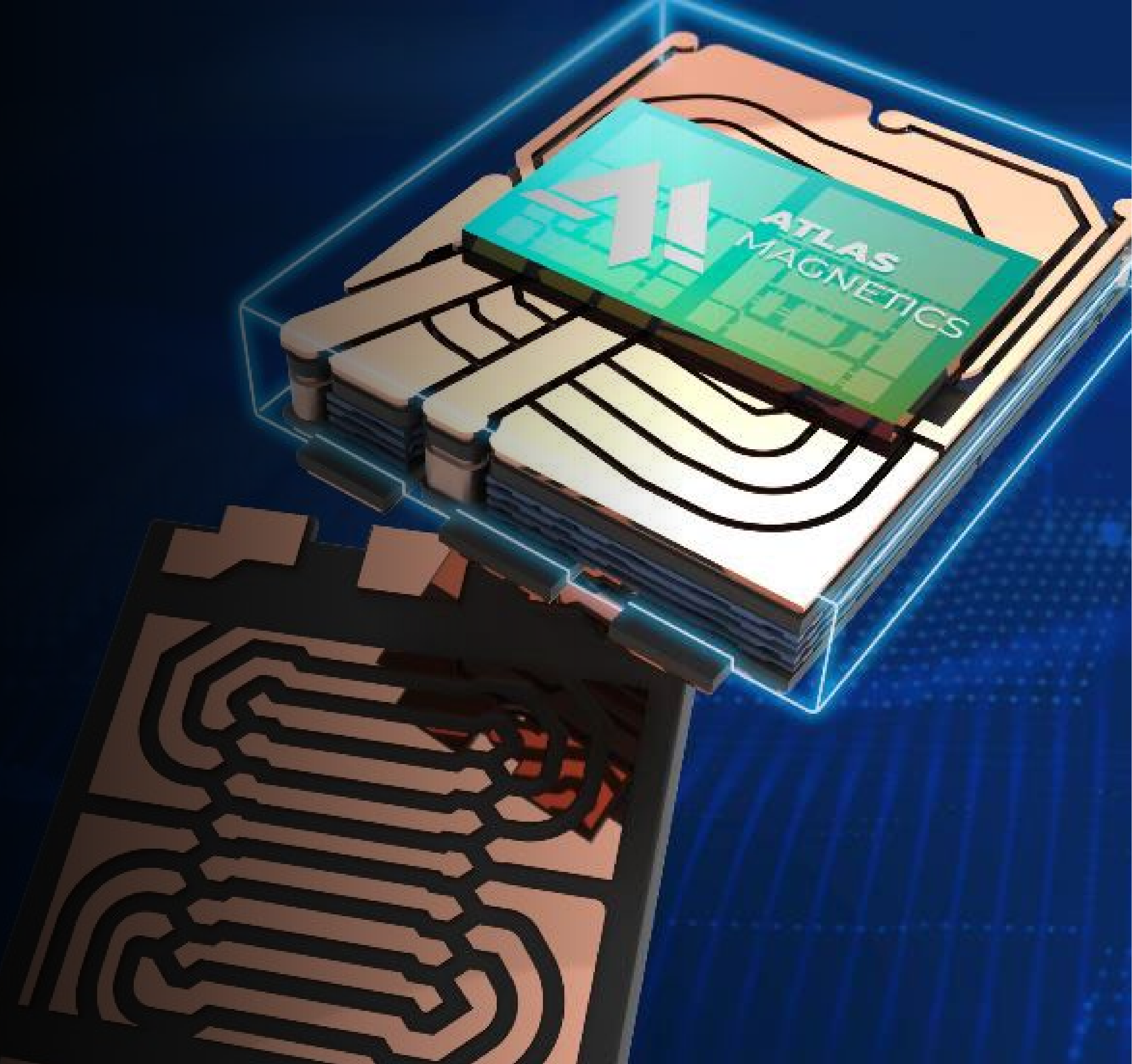
Example of AM’s Metamaterial with 300nm Layering



Nano Layering: 150 to 500 nm

Macro Layering: 15 to 25um

Example: Inductor Built with Advanced Packaging



Thin Film Magnetics Brute Force

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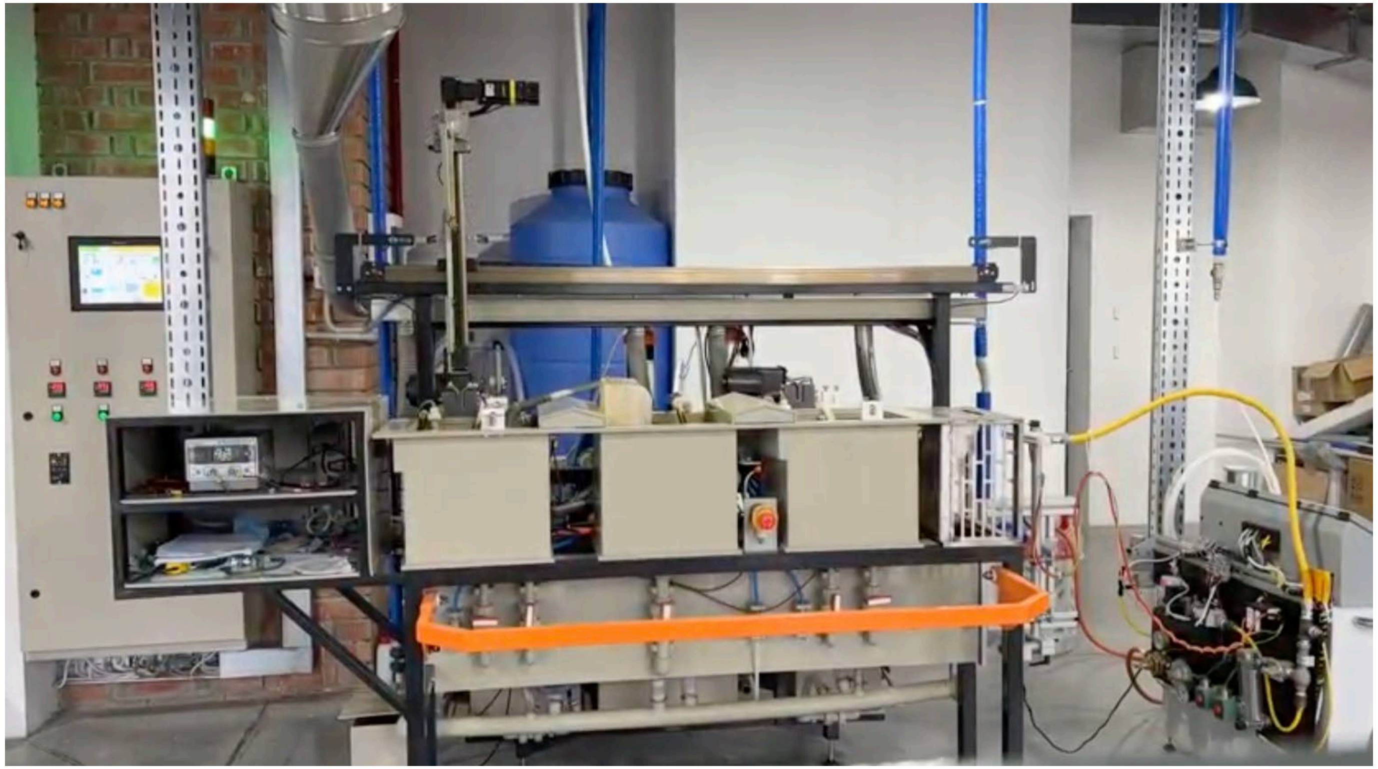
Automated R&D

1,893 Magnetic Thin Film Experiments over a 3-year period

Magnetic Thin Film development is like solving a 17-variable equation: there's no substitute for a lot of data.

Old research papers include helpful hints like "the surface should be shiny and pit free", "more molasses is better".



AM builds our own deposition equipment as cost and time barrier to entry

Electroplating Machine V1 – December 2024

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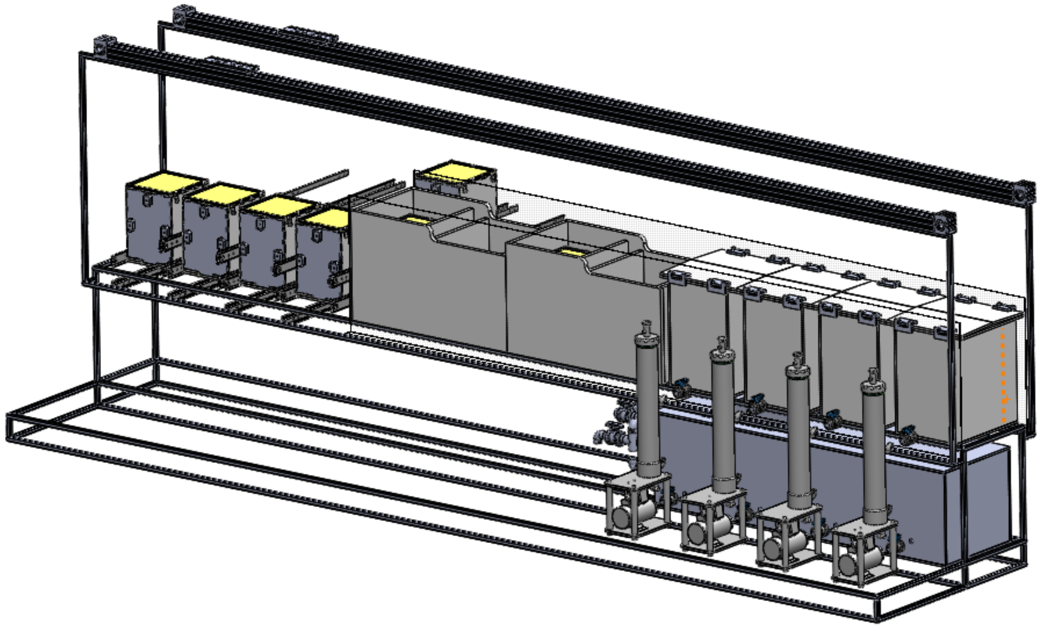
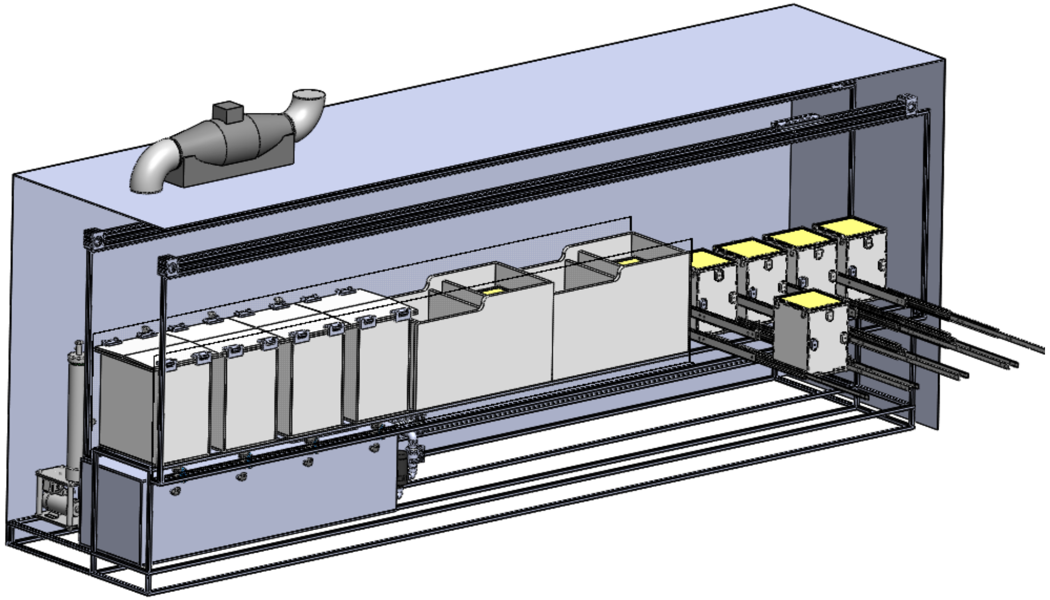
Etching Machine – Coming July 2025





APEC – Thin Film Magnetics -- Results

Material Science

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Atlas Magnetics uses electroplated NiFe and CoNiFe as our fundamental magnetics material. These materials have been well researched for decades.

126 *BELL SYSTEM TECHNICAL JOURNAL*

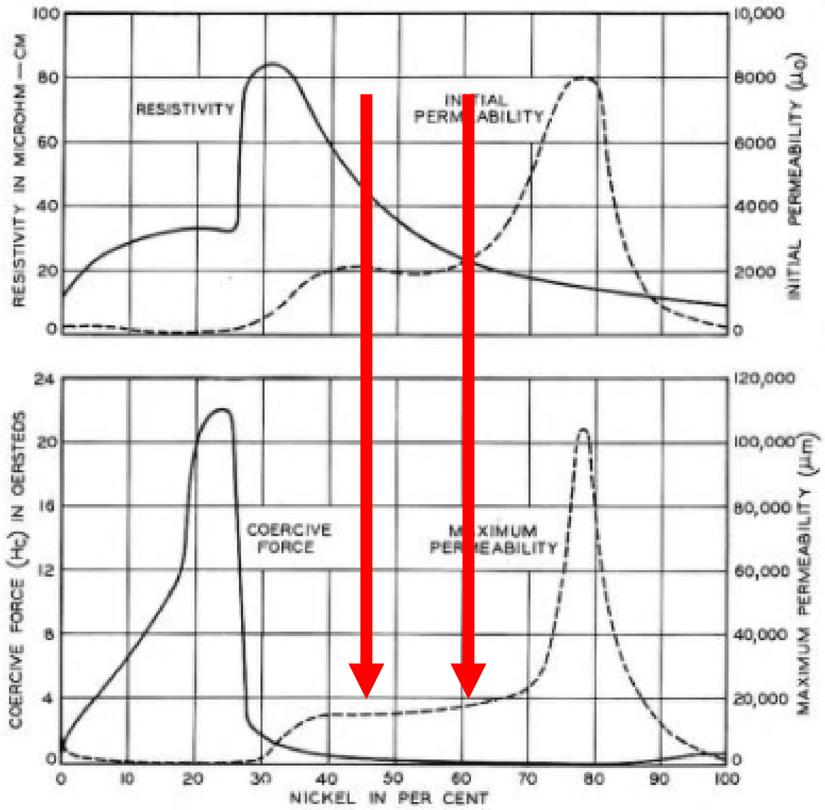

Fig. 8—Resistivity, initial and maximum permeabilities, and coercive force of iron-nickel alloys.

Table 3.13 Properties of NiFe and CoFe Alloys

	p (μΩ cm)	J_s (T)	H_c (A/m)	μ_{max} × 1000	
Fe64Ni36	75	1.3	40	20	Invar
Fe50Ni50	45	1.6	7	15	Isoperm
Fe52Ni48	45	1.6	8	180	
Fe44Ni56	35	1.5	1	300	
Fe20Ni80	16	1.1	0.4	100	Permalloy
Fe16Ni79Mo5	60	0.8	0.4	550	Supermalloy
Fe16Ni77Cu5Cr2	56	0.75	0.8	500	Mumetal
Fe50Co50	7	2.45	160	5	Permendur
Fe49Co49V2	40	2.4	400	17	Hiperco, vacoflux

Material Science

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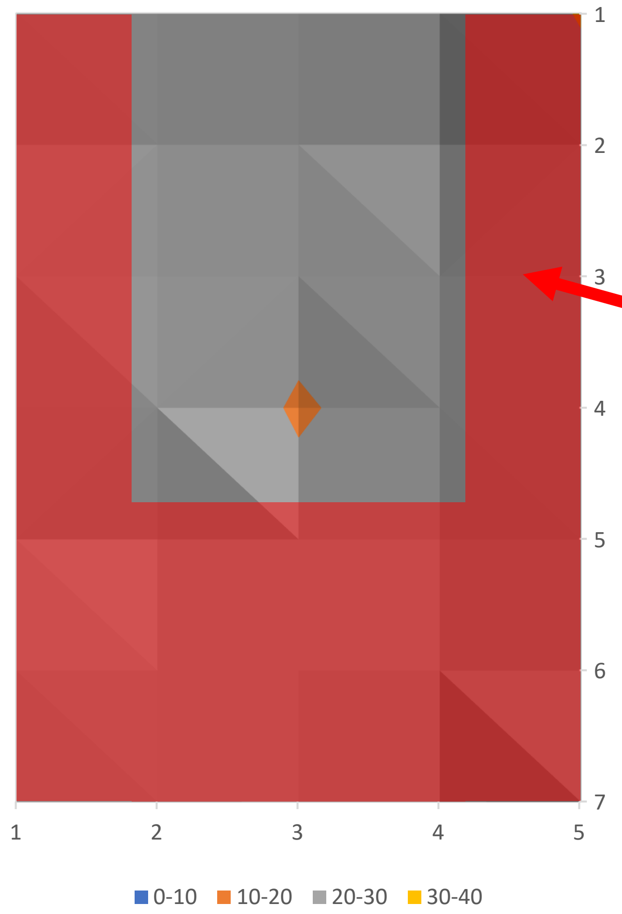
Process prior to Thanksgiving 2024

Production Machinery

10026-M Thickness(um) Map



Terrible plating uniformity,
Areas in red <20% yield

Material Science

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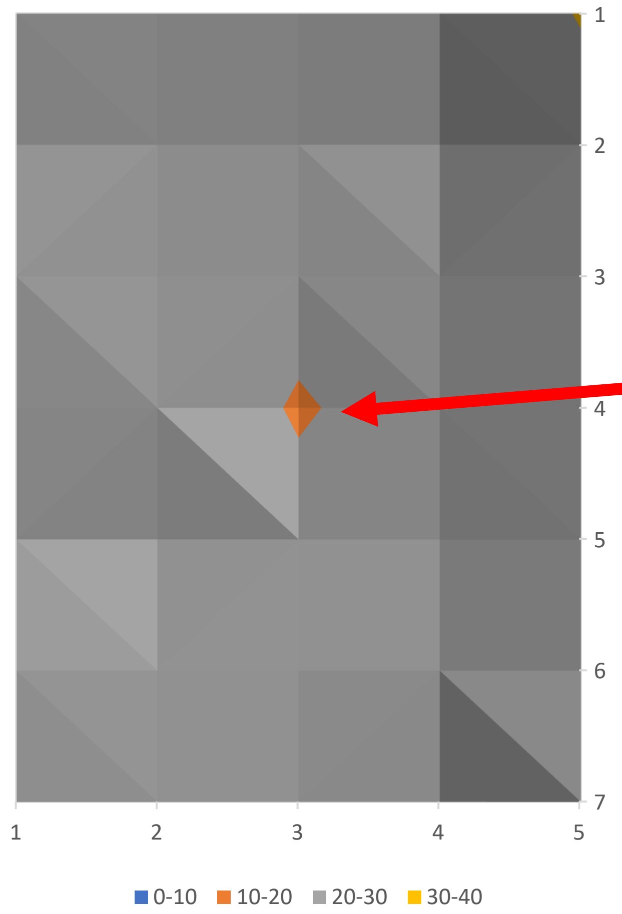
New electroplating machine process variation for thickness

10026-M Thickness(um) Map



Too thin in very center will equal <1% yield issue.

Otherwise, the 540mm x 610mm panel is better +/- 20% thickness

For 100m x 100mm the thickness variation is +/-10%

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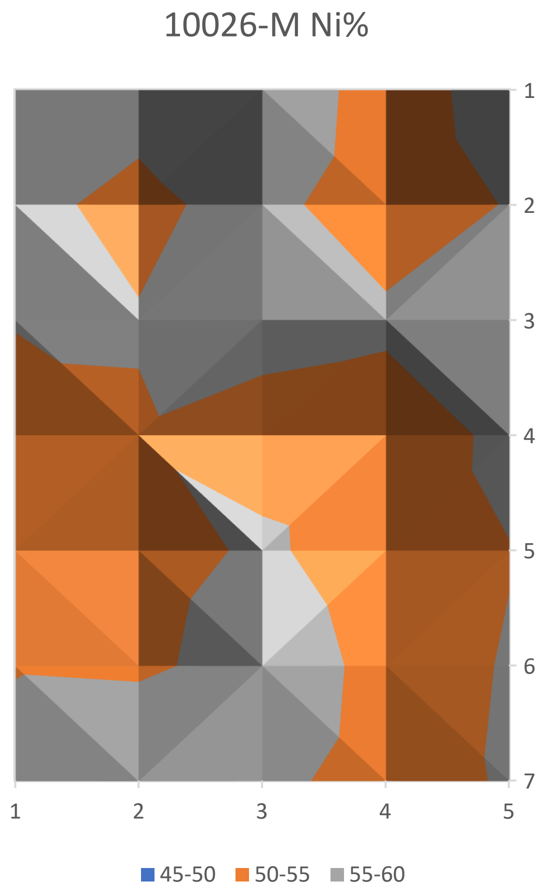
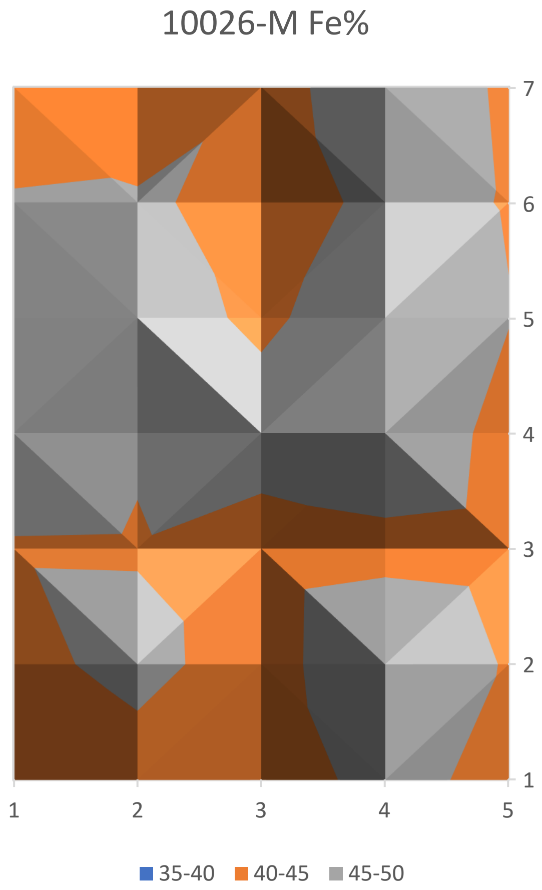
New electroplating machine process variation for % alloy





Entire Panel keeps %Ni , %Fe alloy within spec

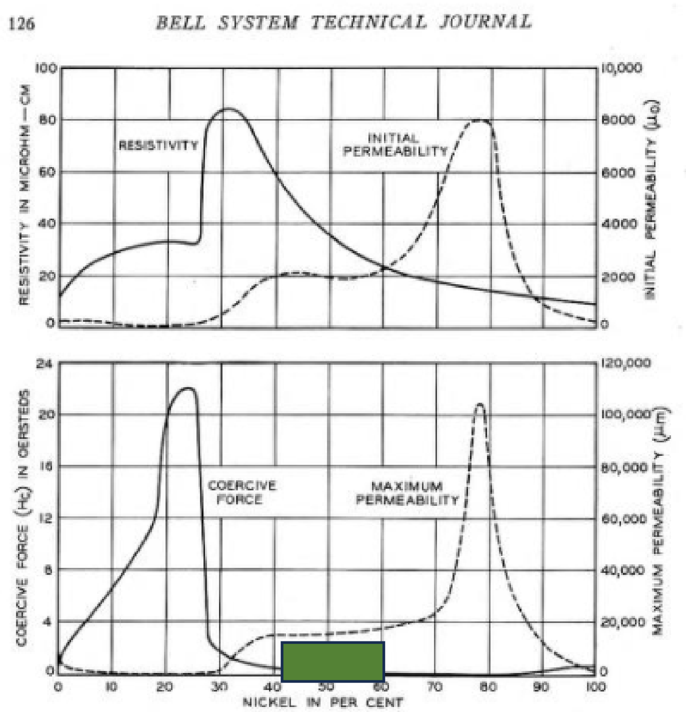


Fig. 8—Resistivity, initial and maximum permeabilities, and coercive force of iron-nickel alloys.

Material Science

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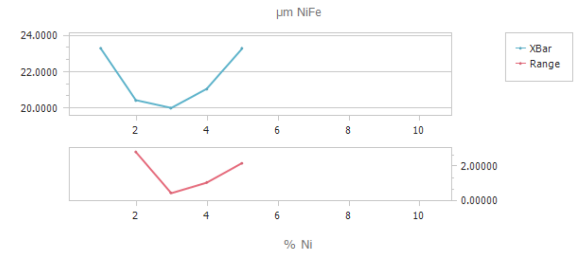
Atlas Magnetics uses our Bowman XRF in Reno, NV and Lviv, Ukraine to determine the alloy percentages and thickness uniformity

Sample 1024, Lviv

Sample ID 11024-L **MES** 27

Analysis Results

		1		
		µm	%	
	Result	NiFe	Ni	Fe
	1	23.3172	43.0218	56.9782
	2	20.4507	43.1248	56.8752
	3	20.0216	43.2169	56.7831
	4	21.0730	43.2450	56.7550
	5	23.2857	43.2670	56.7330
Mean		21.6296	43.1751	56.8249
Min		20.0216	43.0218	56.7330
Max		23.3172	43.2670	56.9782
Range		3.2957	0.2452	0.2452
StdDev		1.57132	0.10138	0.10138
% StdDev		7.26465	0.23482	0.17841
Cp		----	----	----
Cpk		----	----	----
Cg		0.0000	0.0000	0.0000
Cgk		----	----	----



Altas has an extensive database of NiFe and CoNiFe alloy samples.

Proven variability range in a 10cm x 10m panel:

+/-10% in thickness

~0.245% variance in alloy % on the

Matching Error is almost entirely magnetic thickness variation

Material Science

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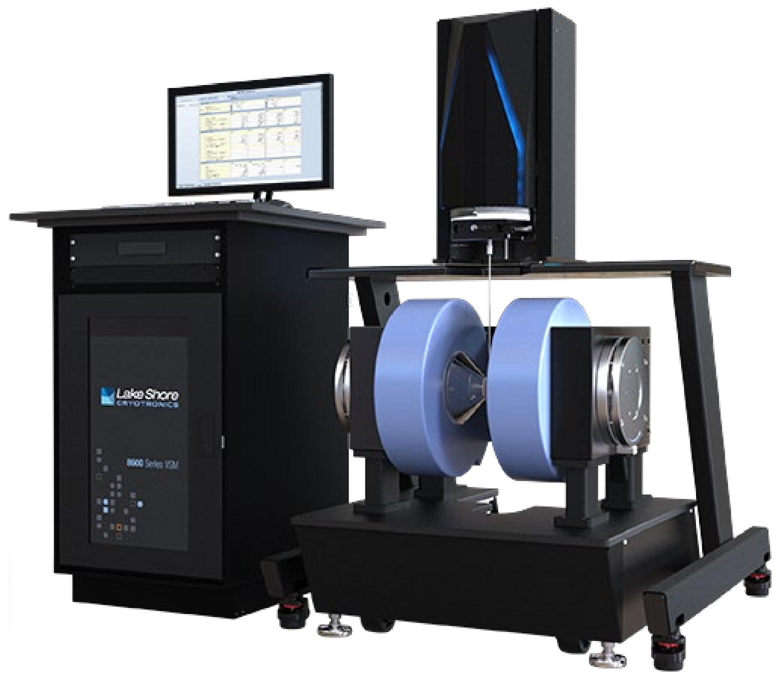
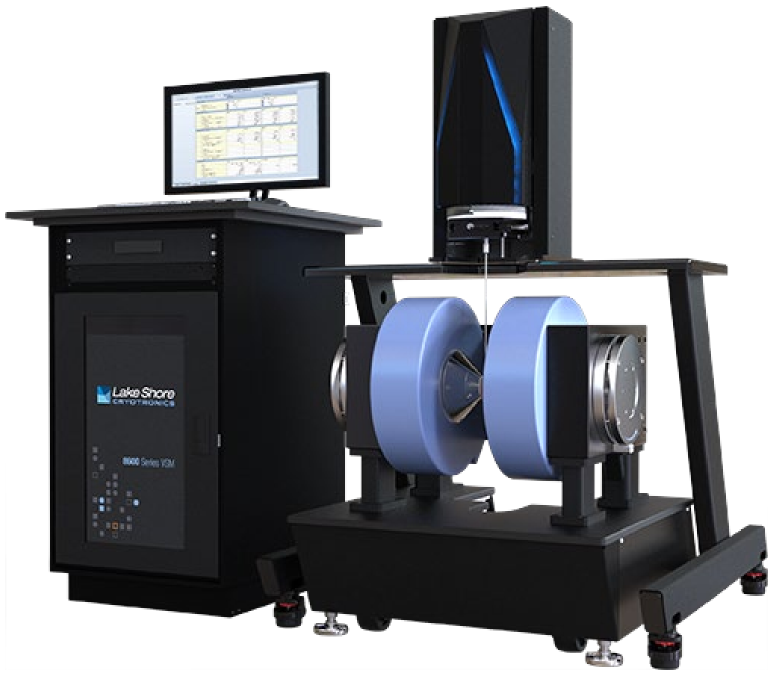
Atlas Magnetics uses our Lakeshore VSM in Reno, NV to determine the MH curve and other key magnetic performance parameters



#RUN ON SOFTWARE VERSION:	
	1.6
#FIELD CONFIGURATIONS	
Magnet: EM4-CSB	
Power supply: LS643	
Head amplitude: 100%	
Gap settings: Gap 2 - RT B	
Coil set name: 86-LC	
Coil set serial number: A13N7	
Coil set balance number: 0.05	
Moment X calibration value: -21.8701204067101 emu/volt	
Moment X calibration field: 5000 Oe	
Moment X calibration expected moment: 6.92 emu	
Moment X calibration standard ID:	
Moment X calibration comments:	
#SAMPLE SETTINGS	
ID: 10353-R 23	
Volume: 400.700E-6 cm^3	
Area: 196.350E-3 cm^2	
Mass: 1.67396E-3 g	
Demagnetization factor: 0.00000 in CGS	

Sample Parameters

Material Science: Source of AM's MH Curve



Sample Characteristics of Sample "a":
Perm of 211, Coercivity <1, and a Bsat of >2.3T

#EXTRACTED PARAMETERS			
Coercivity: 0.844852508221148 Oe			
Saturation magnetization (4pM	B-H) : 23170.7358893939 G		
Permeability: 211.951567415629			
START TIME: 07/10/2024 07:59:07.952 PM			
FINISH TIME: 07/10/2024 08:03:19.022 PM			
#DATA: 2 Corrections			
##DATA TABLE Moment (m) [emu]; Flux density; induction (B) [G] vs Internal field [Oe]			
Step	Iteration	Segment	Internal field [Oe]
2	0	0	-0.0021860340713730800
2	0	0	1.2574309784947400
2	0	0	2.2619783580703800
2	0	0	3.2802774981277200
2	0	0	4.2904335969070500
2	0	0	5.2913186361743100
2	0	0	6.2978024486390000
2	0	0	7.3064603769654300
2	0	0	8.3214523793280500
2	0	0	9.3142016677654900

The VSM takes the MH (BH) curve from +saturation to –saturation. While the VSM is extremely accurate, it doesn't give magnetic performance over frequency. AM's electroplating matches most published papers on NiFe and CoNiFe.

Material Science: Hard Easy Axis

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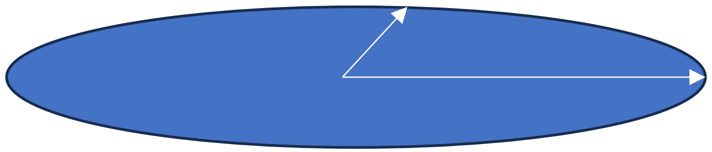
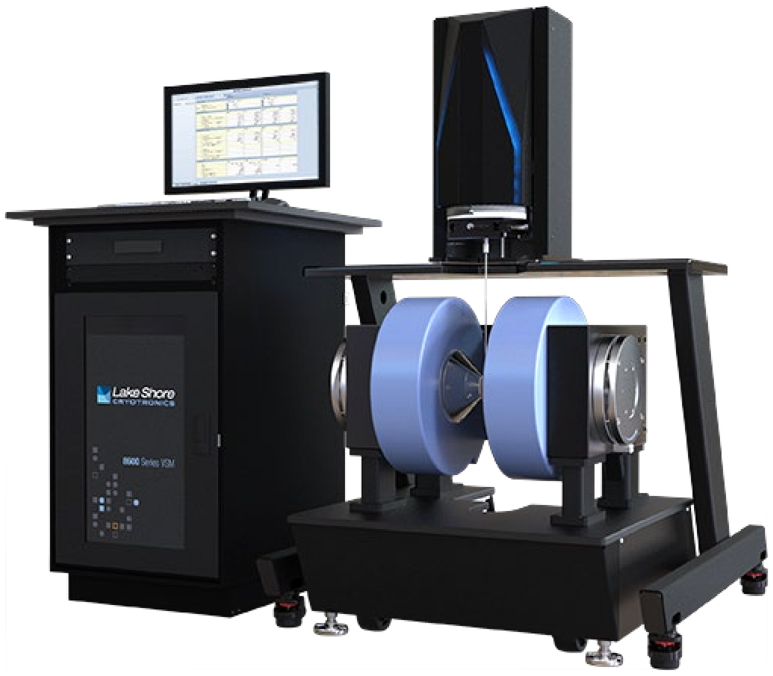




Reno Sample 503

#22

	AVG	0 deg	45 deg	90 deg	135 deg
Oe	**18.66875**	18.76	18.758	18.546	18.611
Bsat	**2.43325**	2.395	2.417	2.467	2.454
Perm	**136.11525**	134.07	134.609	137.807	137.975

#19 (max 500Oe)

	AVG	0 deg	90 deg
Oe	**19.929**	19.881	19.977
Bsat	**1.975**	1.987	1.963
Perm	**169.664**	170.058	169.27

Reno Sample 584

#19 (max 75Oe)

	AVG	0 deg	90 deg
Oe	**16.387**	16.26	16.514
Bsat	**1.2585**	1.263	1.254
Perm	**169.986**	170.324	169.648

Reno Sample 585

#19 (max 75Oe)

	AVG	0 deg	90 deg
Oe	**3.2085**	3.214	3.203
Bsat	**1.121**	1.127	1.115
Perm	**213.346**	213.951	212.741

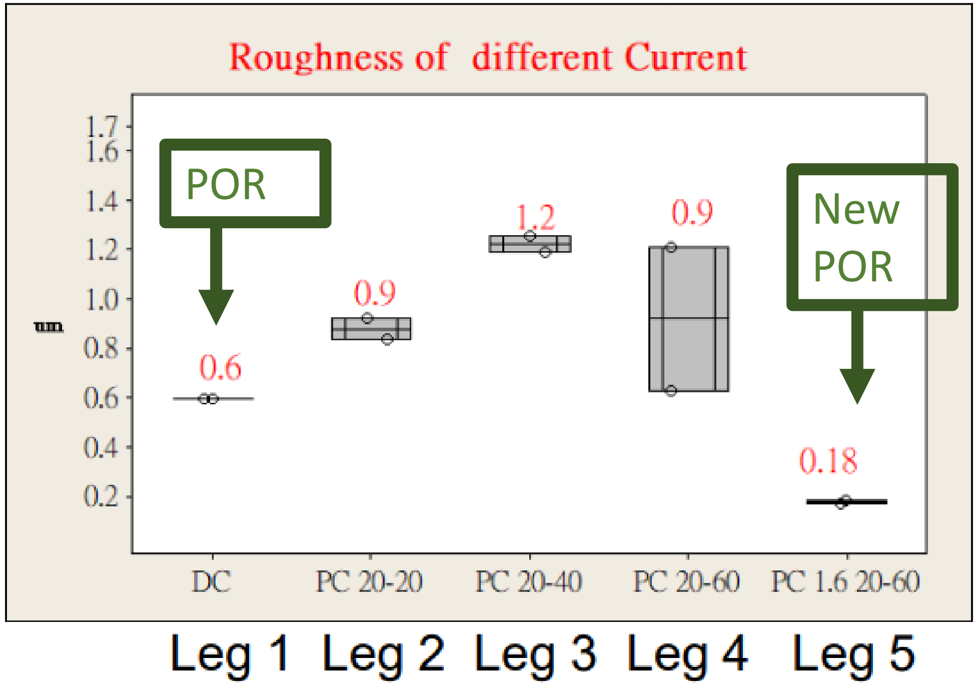
Permeability is stable over a wide power range and varies little based on sample orientation. Atlas Magnetics does not currently use magnetics directed electroplating methods since Coercivity drops significantly at ½ Bsat

Material Science

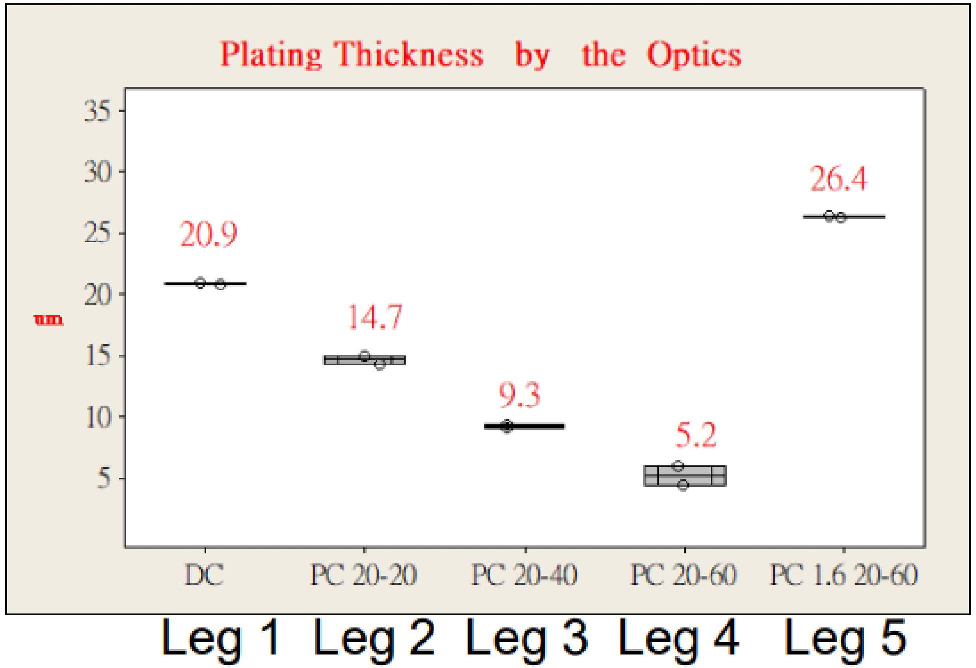
Atlas Magnetics does not model magnetic surface roughness, but we monitor and minimize

Test Stamps

Roughness



Thickness



Quick Aside > Material Science – Copper is Great

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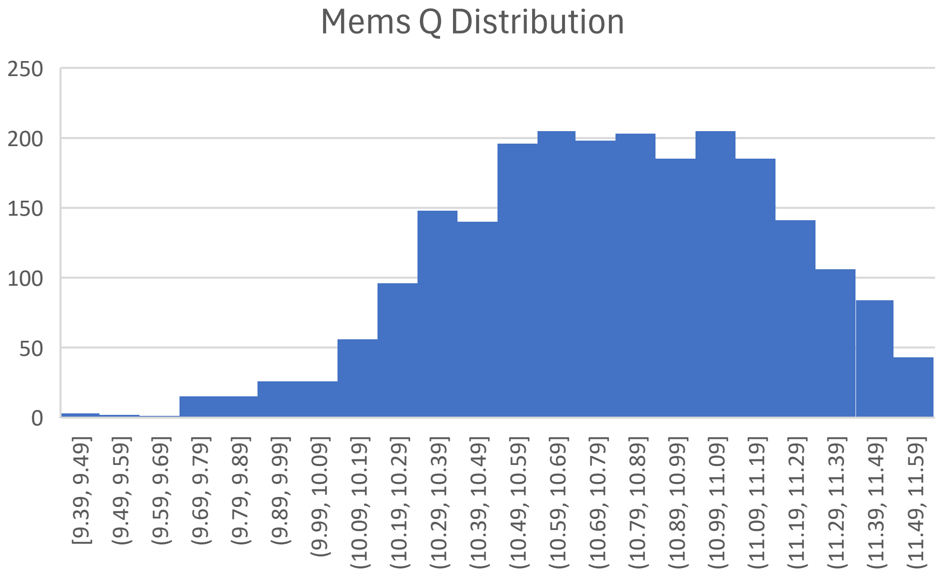
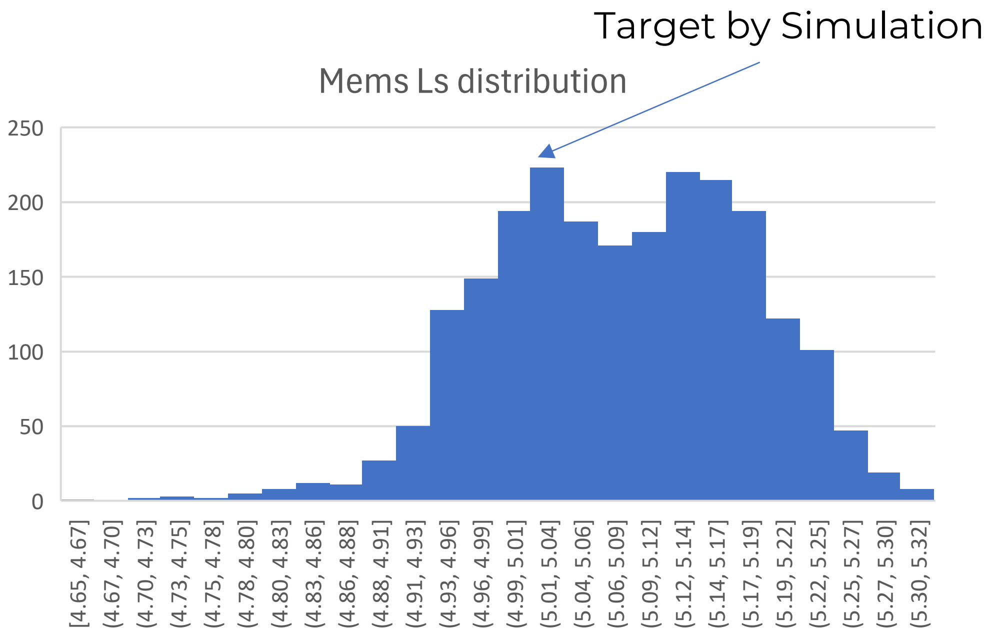
Statistics on >2,280 Copper Coils – pre-Magnetics



+/-7% over from near DC to GHz



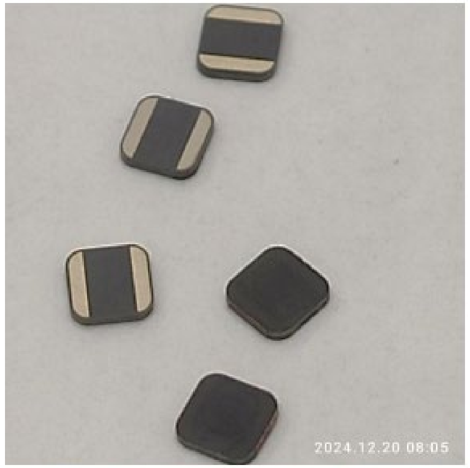
+/-5% over from near DC to GHz

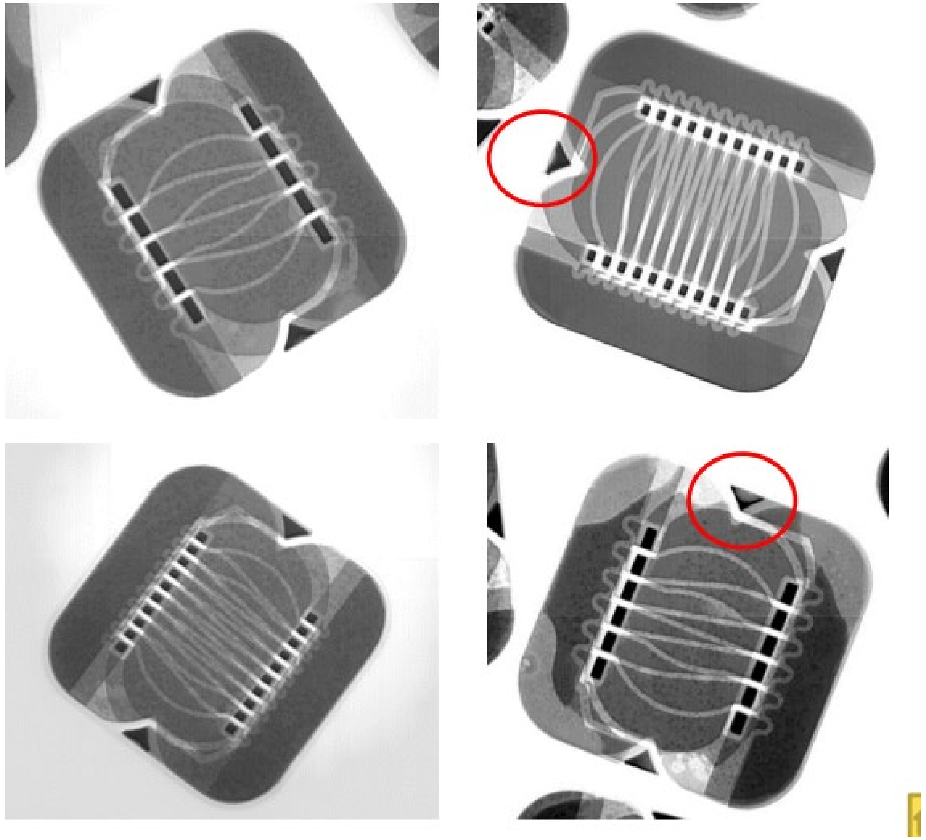
Ansys Copper Simulation and Actual Copper Performance: Quite Accurate

Ansys Air Core Q and Actual Air Core Q Performance: Quite Accurate

Material Science - Copper

AM5P202005-XFL				
Inductor PN:	**# of Loops**	**Inductance, H**	**DCR, mΩ**	**PPt Part Number**
AM5P202005-3NIFE	5,6,7,9,10,11	200,300,410,670,830,1000n	21,32,47,90,105,120	A350071D





47 mohm target → 45 to 52

32 mohm target → 32

Material Science – Seed Layer Problem

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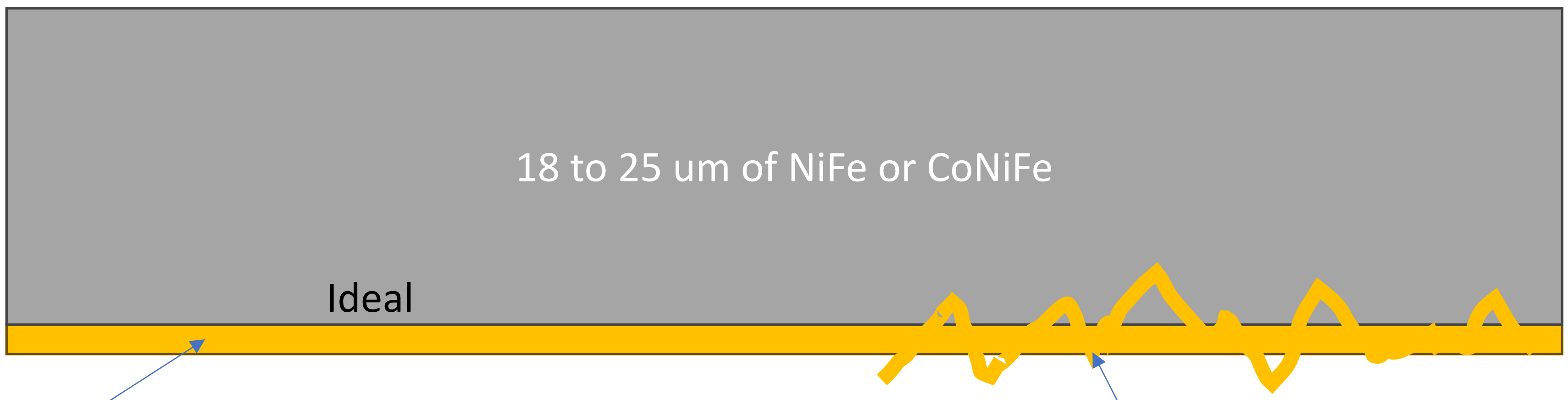

1. Process of Record is a 0.6um Electroless Copper base for the magnetic material – becomes cathode to electroplate the magnetics

2) This 0.6um layer is difficult to model because it's placed on a 1-3um Ra surface.

3) Copper is a poor material for Magnetic performance

Material Science – Seed Layer

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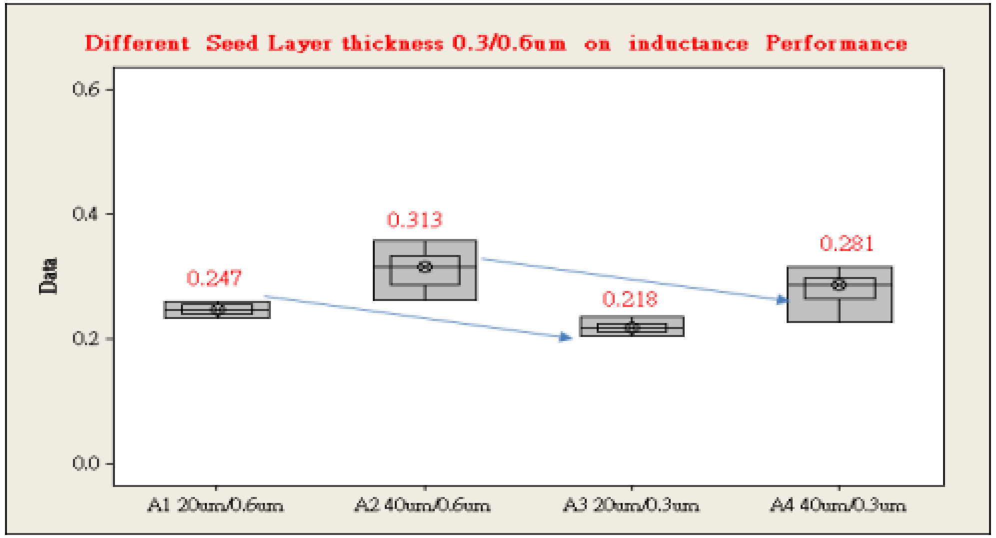
Inductance:



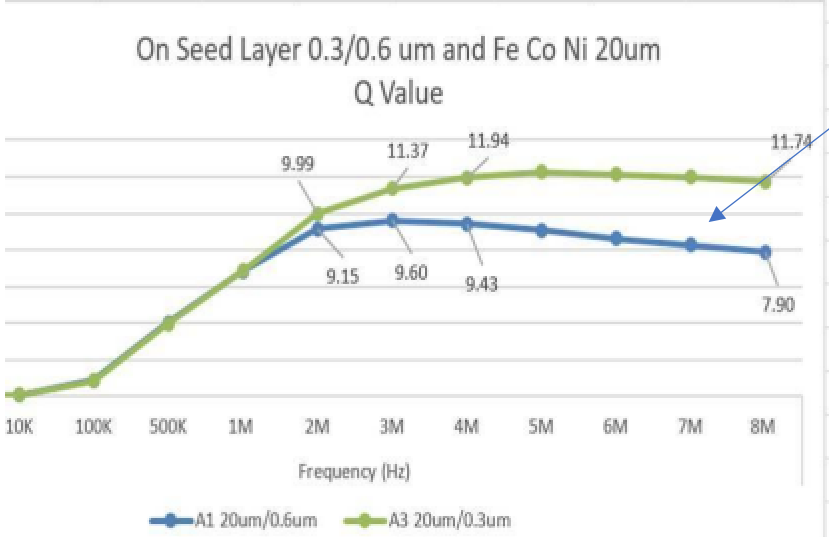
1. The inductance of seed layer 0.6 um is higher than 0.3 um.

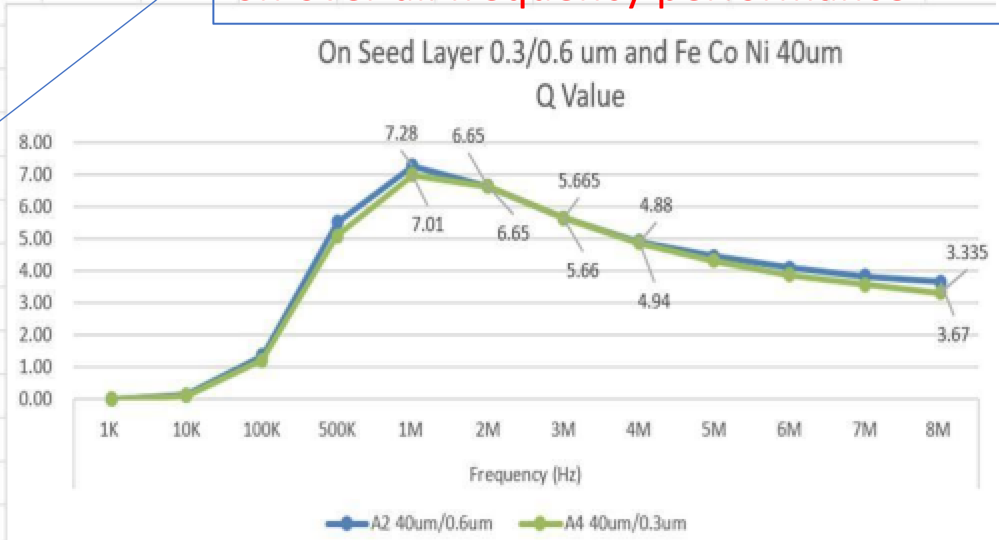
2. Using 20um CoNiFe, the Q value of seed layer 0.3um is much better than 0.6 um after 2M Hz

3. There is no significant difference of Q btw 0.3um and 0.6um by 40um CoNiFe

Cu Seed Layer has a dramatic negative impact on over all frequency performance

Q-Value:

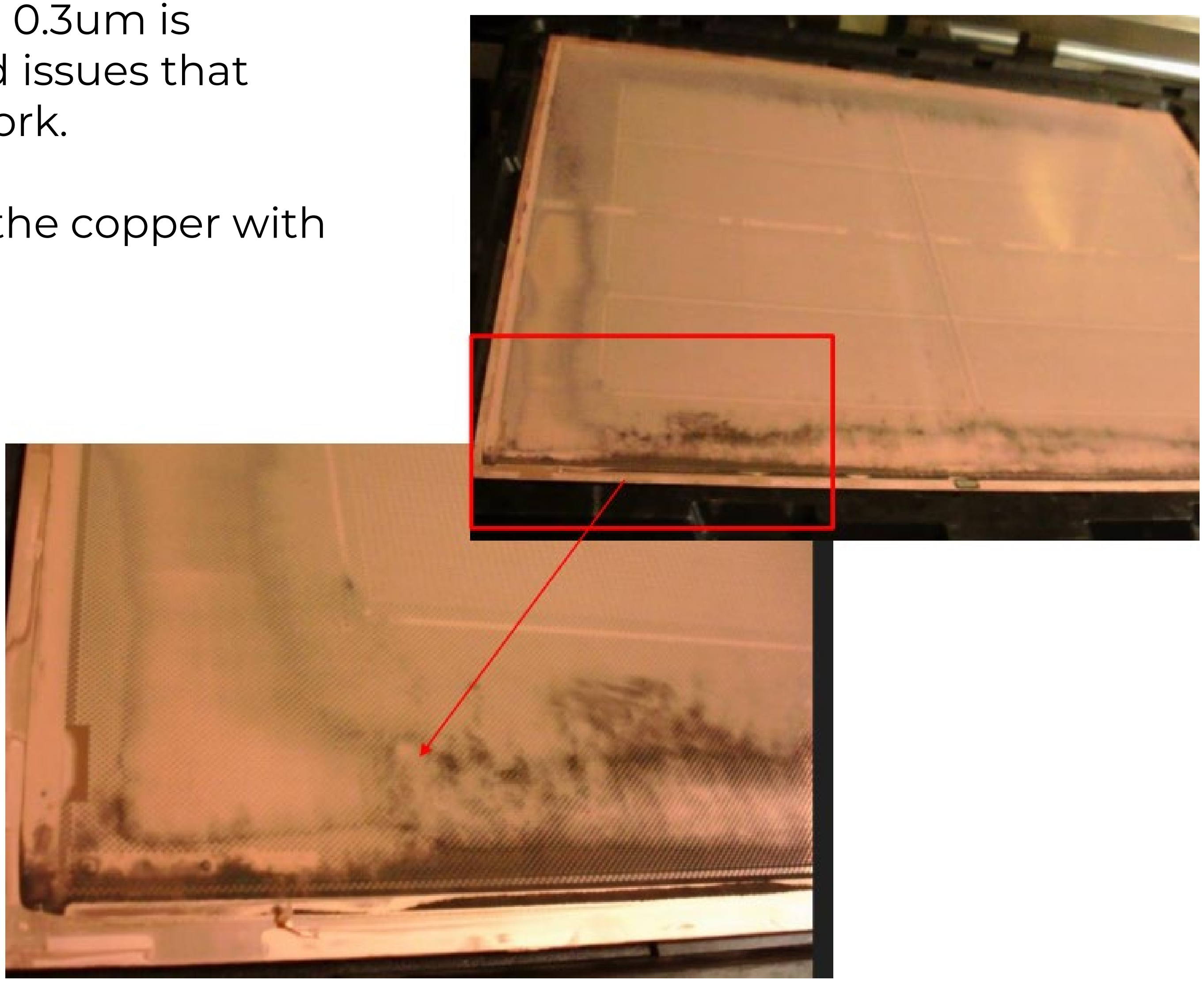




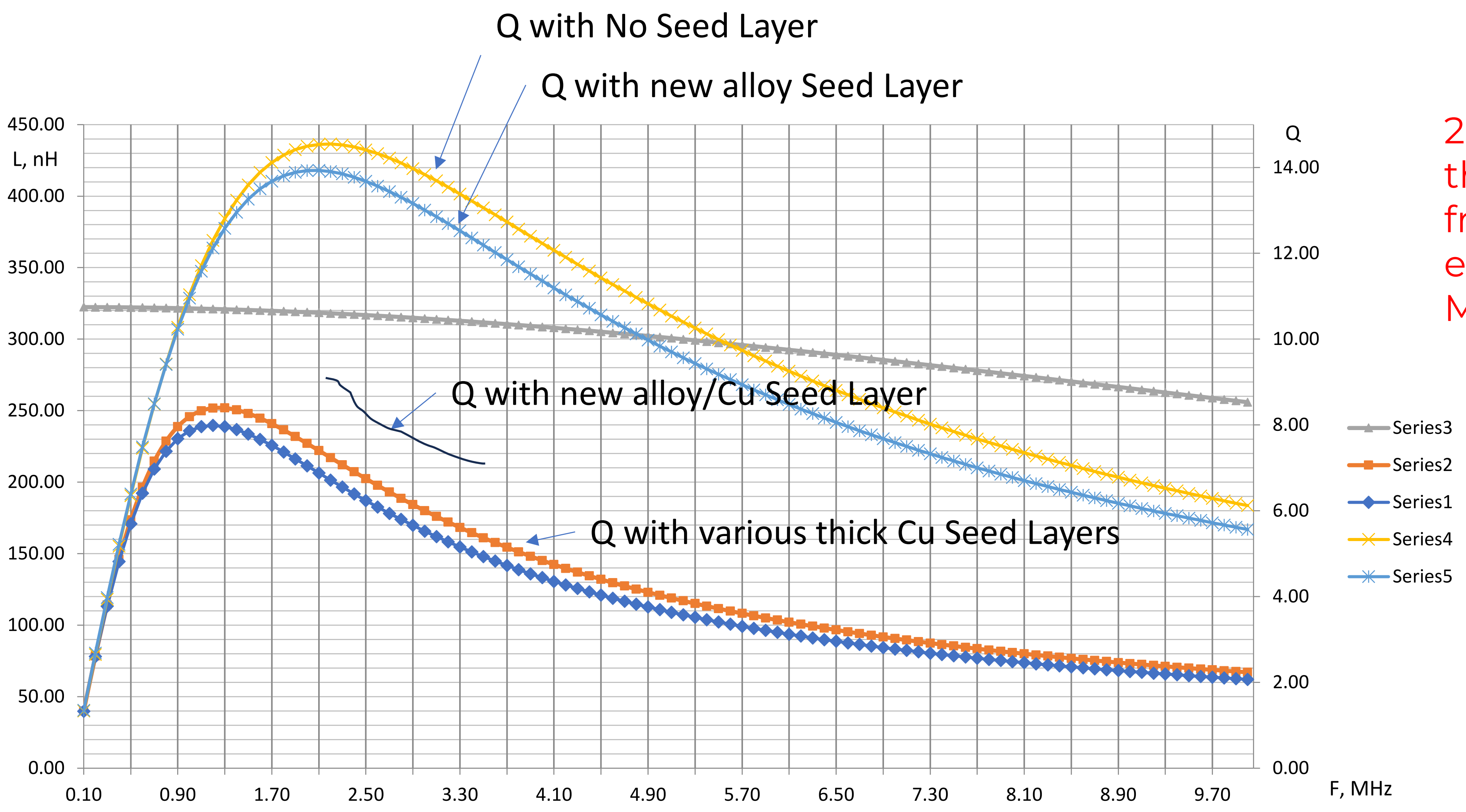
Material Science – Seed Layer Problem

Simply thinning the copper ½ to 0.3um is possible but results in some yield issues that can be solved but take a lot of work.

Our next step in Q1 is to replace the copper with a new alloy.



Material Science – Seed Layer

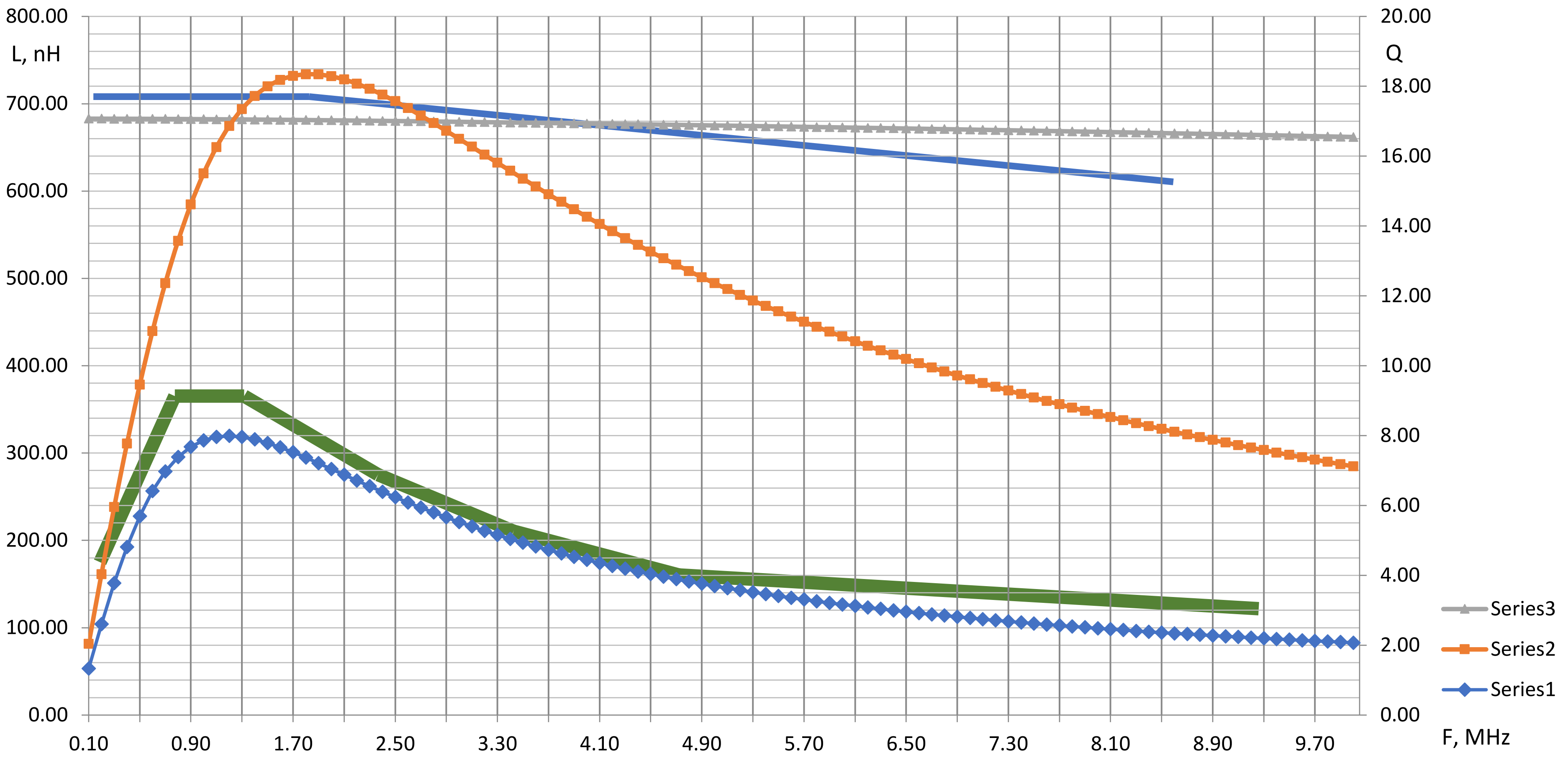


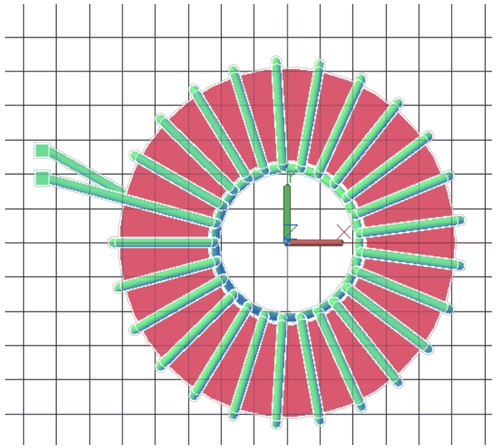
20 um thick, adjusting thinner increases frequency exponentially, 100's MHz is possible.

Correlation to Simulation

Using the VSM parameters and MH curve we model the actual 25 turn research toroid

Assumes 18um and 200 perm





Ansys Inductance is good

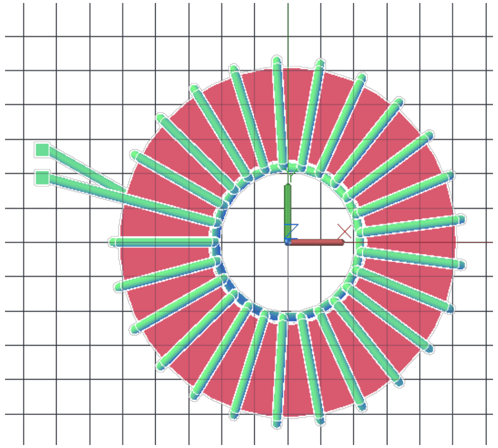
Ansys Q is good but seed layer must be included in model

Correlation to Simulation

Actual Thickness and Frequency Measured data on Sample 850

(20um thickness)

Frequency(Hz)	AC Status	DC Status	Ls	Rs	Rdc	Q	
1000	0	0	7.56E-07	1.39E-01	1.39E-01	0.03	
10000	0	0	7.57E-07	1.40E-01	1.39E-01	0.34	100%
100000	0	0	7.53E-07	1.47E-01	1.39E-01	3.22	100%
500000	0	0	7.47E-07	2.41E-01	1.39E-01	9.72	99%
1000000	0	0	7.39E-07	4.91E-01	1.39E-01	9.47	98%
2000000	0	0	7.20E-07	1.34E+00	1.39E-01	6.74	95%
3000000	0	0	6.97E-07	2.57E+00	1.39E-01	5.11	92%
4000000	0	0	6.70E-07	4.05E+00	1.39E-01	4.16	89%
5000000	0	0	6.42E-07	5.64E+00	1.39E-01	3.57	85%
6000000	0	0	6.14E-07	7.28E+00	1.39E-01	3.18	81%
7000000	0	0	5.87E-07	8.86E+00	1.39E-01	2.91	78%
8000000	0	0	5.63E-07	1.04E+01	1.39E-01	2.73	74%



Thin Film Magnetics Results

- Sample number 11147-L
- Alloy composition, additives are proprietary and not listed
- 24µm

Frequency(Hz)	AC Status	DC Status	Ls	Rs	Rdc	Q		Frequency(Hz)	AC Status	DC Status	Ls	Rs	Rdc	Q	
1000	0	0	4.31E-07	1.40E-01	1.40E-01	0.02	100.0%	1000	0	0	4.43E-07	1.56E-01	1.56E-01	0.02	100.0%
10000	0	0	4.36E-07	1.40E-01	1.40E-01	0.2	101.0%	10000	0	0	4.47E-07	1.56E-01	1.56E-01	0.18	100.9%
100000	0	0	4.36E-07	1.41E-01	1.40E-01	1.94	101.0%	100000	0	0	4.47E-07	1.57E-01	1.56E-01	1.79	100.8%
500000	0	0	4.34E-07	1.68E-01	1.40E-01	8.11	100.6%	500000	0	0	4.46E-07	1.86E-01	1.56E-01	7.51	100.5%
1000000	0	0	4.32E-07	2.42E-01	1.40E-01	11.22	100.1%	1000000	0	0	4.43E-07	2.69E-01	1.56E-01	10.33	99.9%
2000000	0	0	4.26E-07	4.89E-01	1.40E-01	10.95	98.8%	2000000	0	0	4.37E-07	5.48E-01	1.56E-01	10.02	98.5%
3000000	0	0	4.21E-07	8.39E-01	1.40E-01	9.45	97.5%	3000000	0	0	4.30E-07	9.42E-01	1.56E-01	8.61	97.0%
4000000	0	0	4.15E-07	1.28E+00	1.40E-01	8.16	96.1%	4000000	0	0	4.23E-07	1.43E+00	1.56E-01	7.42	95.3%
5000000	0	0	4.08E-07	1.79E+00	1.40E-01	7.18	94.7%	5000000	0	0	4.15E-07	2.00E+00	1.56E-01	6.53	93.6%
6000000	0	0	4.02E-07	2.36E+00	1.40E-01	6.41	93.1%	6000000	0	0	4.07E-07	2.61E+00	1.56E-01	5.87	91.7%
7000000	0	0	3.95E-07	2.97E+00	1.40E-01	5.86	91.6%	7000000	0	0	3.99E-07	3.24E+00	1.56E-01	5.4	89.9%
8000000	0	0	3.89E-07	3.60E+00	1.40E-01	5.43	90.1%	8000000	0	0	3.91E-07	3.89E+00	1.56E-01	5.06	88.1%

+/-3% matching typical, Cpk 1.5 min/max not set yet.

Thin Film Magnetics Results

(AFTER REFLOW)

- Sample number 11147-L
- Alloy composition, additives are proprietary and not listed
- 24μm

Frequency(Hz)	AC Status	DC Status	Ls	Rs	Rdc	Q	
1000	0	0	4.12E-07	1.42E-01	1.43E-01	0.02	100.0%
10000	0	0	4.16E-07	1.42E-01	1.43E-01	0.18	100.8%
100000	0	0	4.15E-07	1.44E-01	1.43E-01	1.81	100.8%
500000	0	0	4.14E-07	1.73E-01	1.43E-01	7.51	100.4%
1000000	0	0	4.11E-07	2.55E-01	1.43E-01	10.13	99.7%
2000000	0	0	4.04E-07	5.28E-01	1.43E-01	9.61	98.0%
3000000	0	0	3.97E-07	9.07E-01	1.43E-01	8.25	96.3%
4000000	0	0	3.89E-07	1.36E+00	1.43E-01	7.19	94.3%
5000000	0	0	3.81E-07	1.86E+00	1.43E-01	6.44	92.3%
6000000	0	0	3.72E-07	2.38E+00	1.43E-01	5.9	90.3%
7000000	0	0	3.65E-07	2.90E+00	1.43E-01	5.53	88.5%
8000000	0	0	3.57E-07	3.41E+00	1.43E-01	5.27	86.7%

+/-10% after reflow , Cpk 1.5 min/max not set yet.

Frequency(Hz)	AC Status	DC Status	Ls	Rs	Rdc	Q	
1000	0	0	4.27E-07	1.57E-01	1.57E-01	0.02	100.0%
10000	0	0	4.31E-07	1.57E-01	1.57E-01	0.17	100.9%
100000	0	0	4.31E-07	1.59E-01	1.57E-01	1.71	100.8%
500000	0	0	4.29E-07	1.91E-01	1.57E-01	7.04	100.5%
1000000	0	0	4.26E-07	2.84E-01	1.57E-01	9.41	99.7%
2000000	0	0	4.18E-07	5.99E-01	1.57E-01	8.76	97.8%
3000000	0	0	4.09E-07	1.03E+00	1.57E-01	7.45	95.8%
4000000	0	0	3.99E-07	1.54E+00	1.57E-01	6.5	93.5%
5000000	0	0	3.89E-07	2.10E+00	1.57E-01	5.83	91.2%
6000000	0	0	3.80E-07	2.67E+00	1.57E-01	5.37	88.9%
7000000	0	0	3.71E-07	3.22E+00	1.57E-01	5.07	86.8%
8000000	0	0	3.63E-07	3.75E+00	1.57E-01	4.86	84.9%

+/-4% matching after reflow , Cpk 1.5 min/max not set yet, moves in the same direction

Core Efficiency – AM in Actual DC/DC System

420nH AM Inductor

$$\frac{128.6\text{mW}}{2.558\text{ V} * 1\text{A}}$$

~5% power loss in the inductor at 3 MHz.

Power Efficiency – AM vs High-performance Discrete

Inductance Error, %	Samples #	Power Losses, mW	Inductance, H
-3.70	1	105.15	4.53E-07
-7.85	2	121.12	4.36E-07
-5.28	3	112.82	4.46E-07
-11.00	4	114.57	4.23E-07
-2.63	5	104.65	4.58E-07
-8.99	6	116.65	4.31E-07
-4.48	7	119	4.50E-07
-5.01	8	106.32	4.48E-07
-4.14	9	117.87	4.51E-07
-7.30	10	109.87	4.38E-07

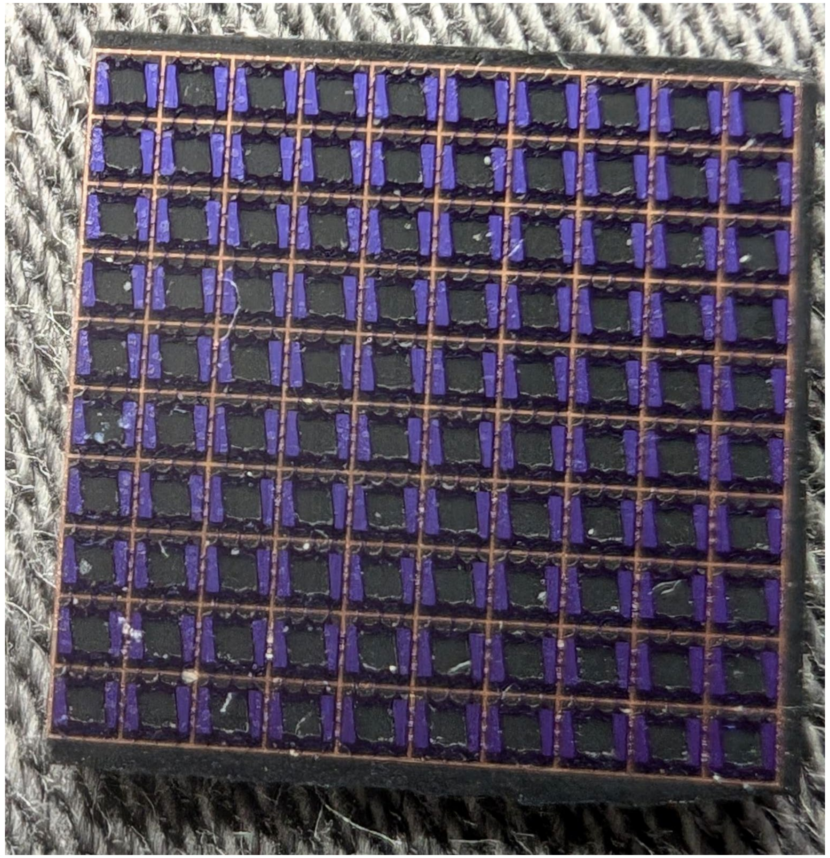
AM not DCR adjusted	128.6	4.20E-07
AM DCR production	**109**	**4.20E-07**

Very little power loss difference between AM integrated and high- performance discrete inductor for a similar XY size, nH, DCR inductor. AM is far thinner!

Many Applications (Materials + Silicon)

Massive array of inductors

10 x 10 inductor array



AM Produces Standard Passives Well

World's thinnest inductors at equivalent performance

ATLAS MAGNETICS

The End