Tyndall National Institute
Institiúid Náisiúnta

Nano-magnetics for high efficiency power supplies

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Outline

- Collaborative Center for Applied Nanotechnology
- Motivation
- Analysis of Magnetic core losses
- Tyndall's approach for improving Nanocrystalline soft magnetic core performance
- Post-processed thin film core vs ferrite core
- Conclusions

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Open Innovation that actually Works!

Turning Materials into Products through supply-chain based open innovation

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CRANN 1

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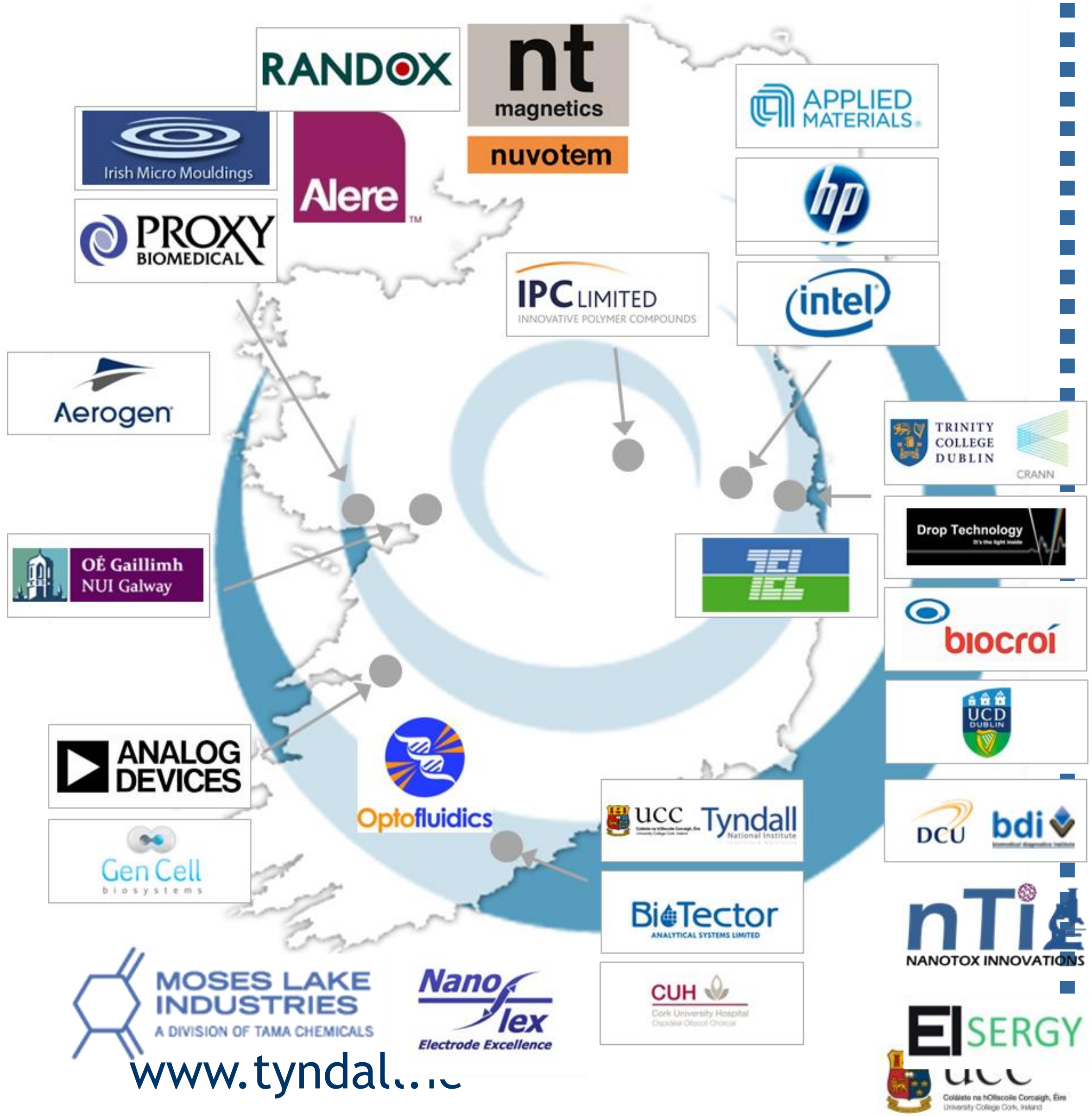
Current CCAN members

- 21 companies, 5 universities
- 14 SMEs, 7 multinationals
- Mix of Irish & International Life Science and ICT companie
- All require nano-enabled materials development
- More at www.ccan.ie



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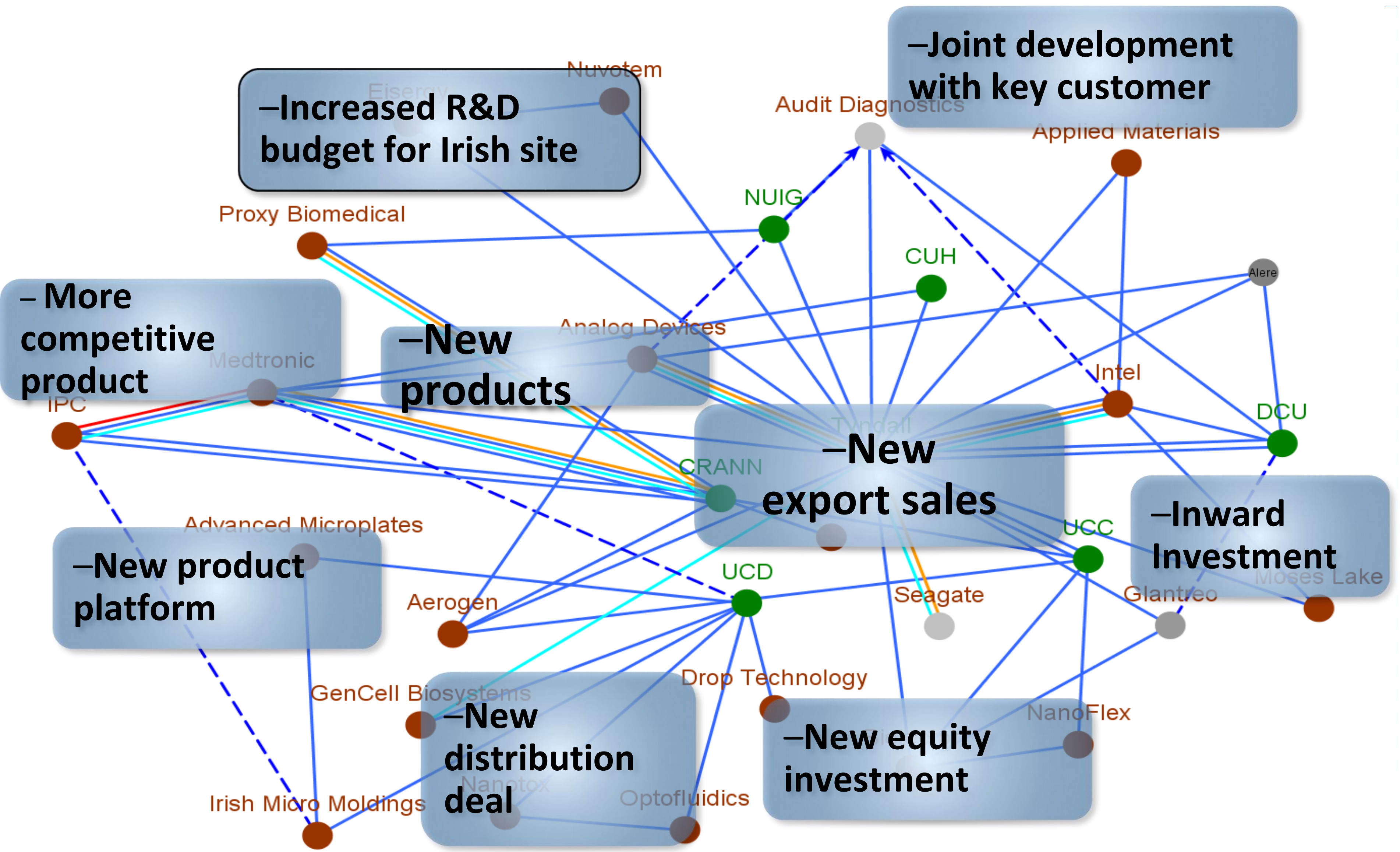
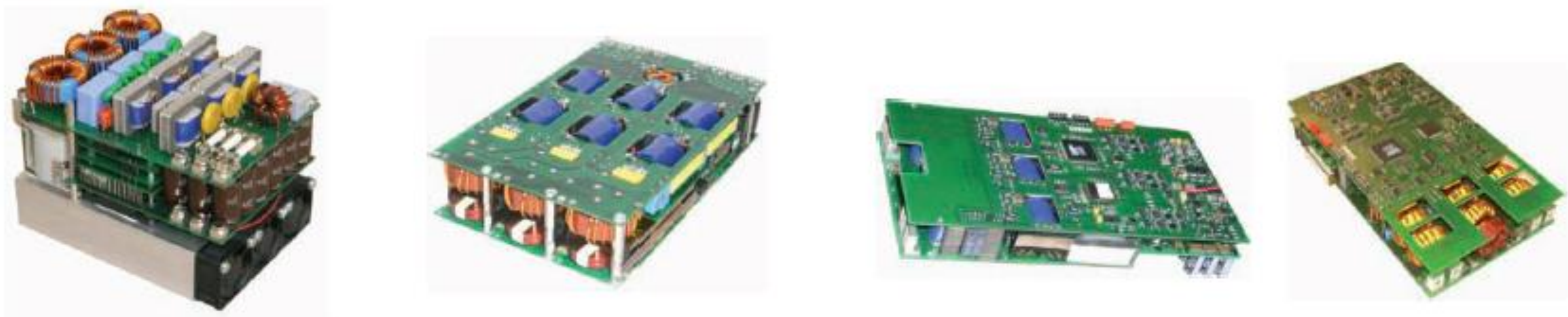
Innovation Network through mini-supply chains



Motivation

- Desired performance: high efficiency and power density
- Advances in power switches & controllers, GaN, SiC…
  - frequency ↑, inductance required ↓
- Magnetics 'key' to growth of power electronics
- Magnetic materials key challenge for advancing power magnetics technology



$f_P =$	72kHz	250 kHz	500kHz	1MHz
$\rho =$	4.5 kW/dm^3	10 kW/dm^3	13 kW/dm^3	14 kW/dm^3

*Kolar et al**

- **Key Applications:**
  - **Power Factor Correction**
  - **Flyback**
  - **Buck**
- **Complements advances in semiconductor technologies including wide-band gap devices.**

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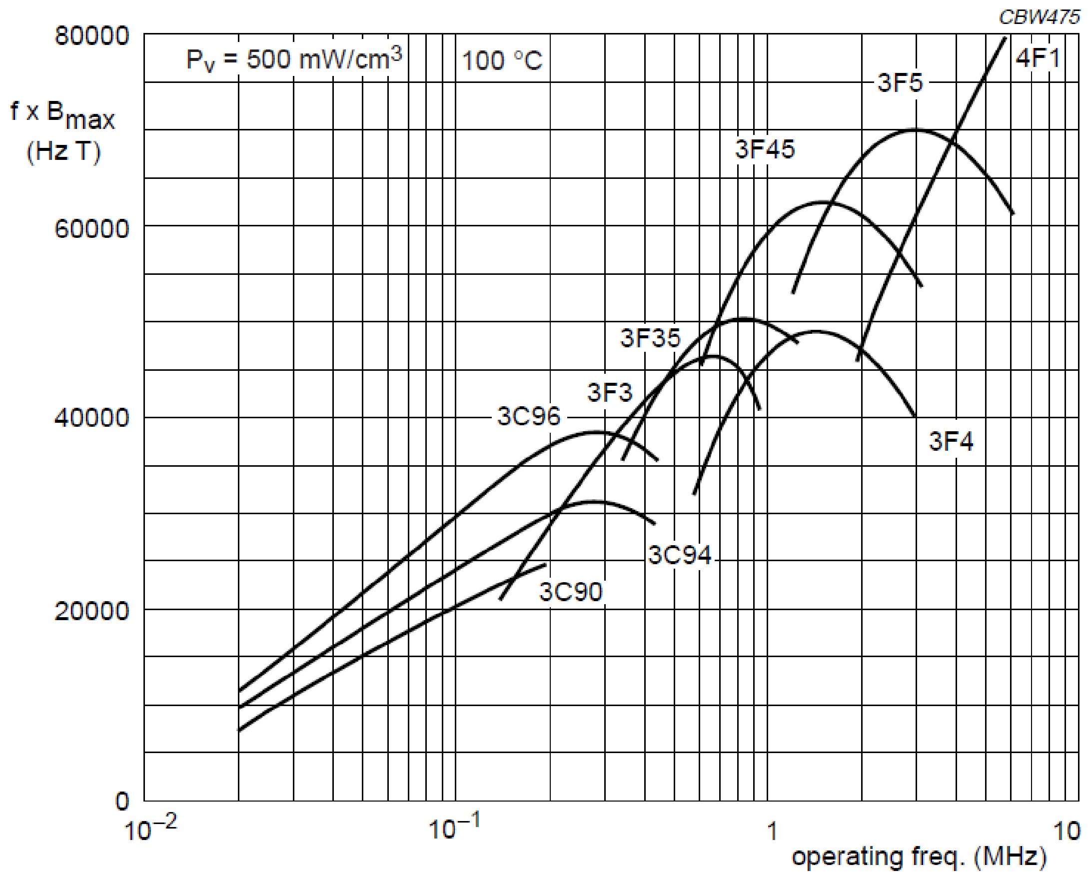
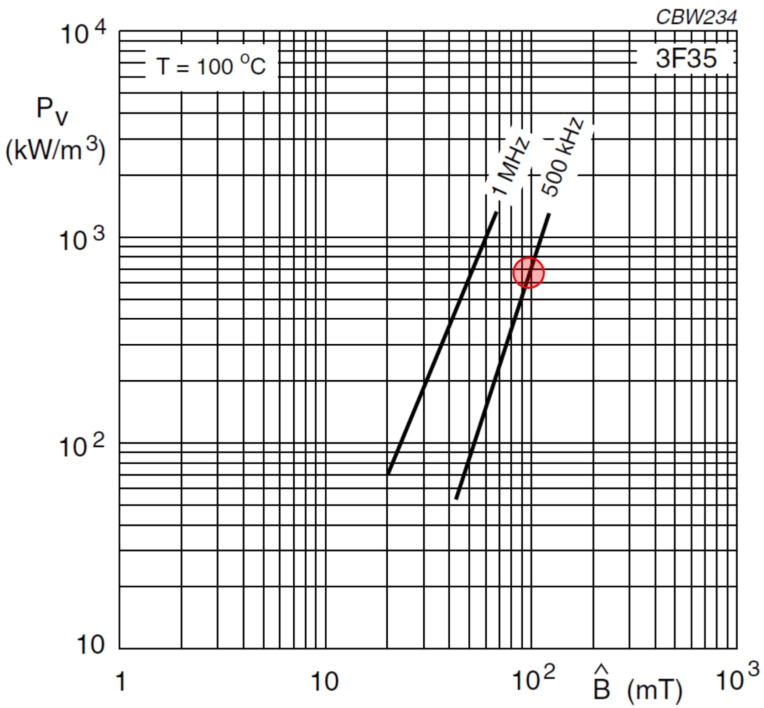
Ferrite Performance



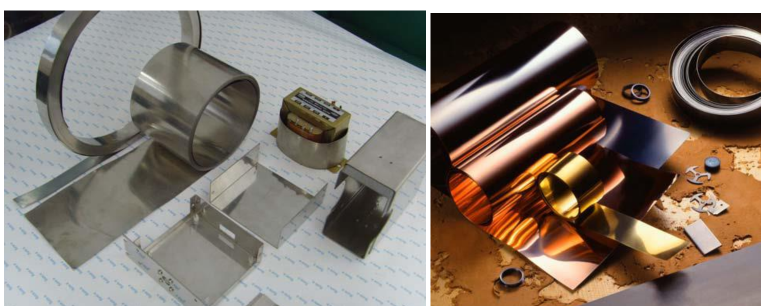


Performance Bench Mark:

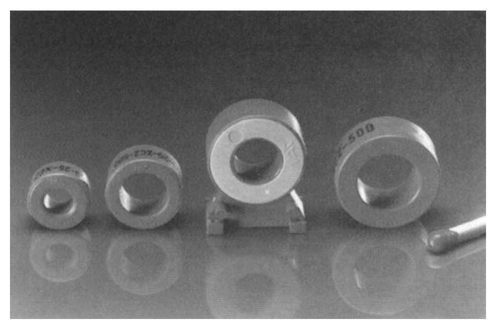
700 kW/m^3 @500kHz & 0.1T B_{peak}

Review of Soft Magnetic thin films

- Objective- to replace ferrite cores with high flux density thin film material with improved performance
- Three different soft magnetic thin films evaluated
  - Electrodeposited research based thin films (NiFe, CoP etc)- thickness- <5 μm
  - High permeability commercial thin film alloys (NiFe-Esong, Goodfellows)- thickness- <5 μm
  - Nanocrystalline thin films (Vacuumschmelze, Toshiba)- thickness- >21 μm
- Toroidal samples prepared with OD- 7.7 mm, ID- 7.5 mm along with 25 turn copper primary & secondary windings
- Performance of thin films compared to ferrite (3c90) at 100 kHz



Commercial magnetic thin films



Amorphous and nanocrystaline tape-wound cores

Review of Soft Magnetic thin films

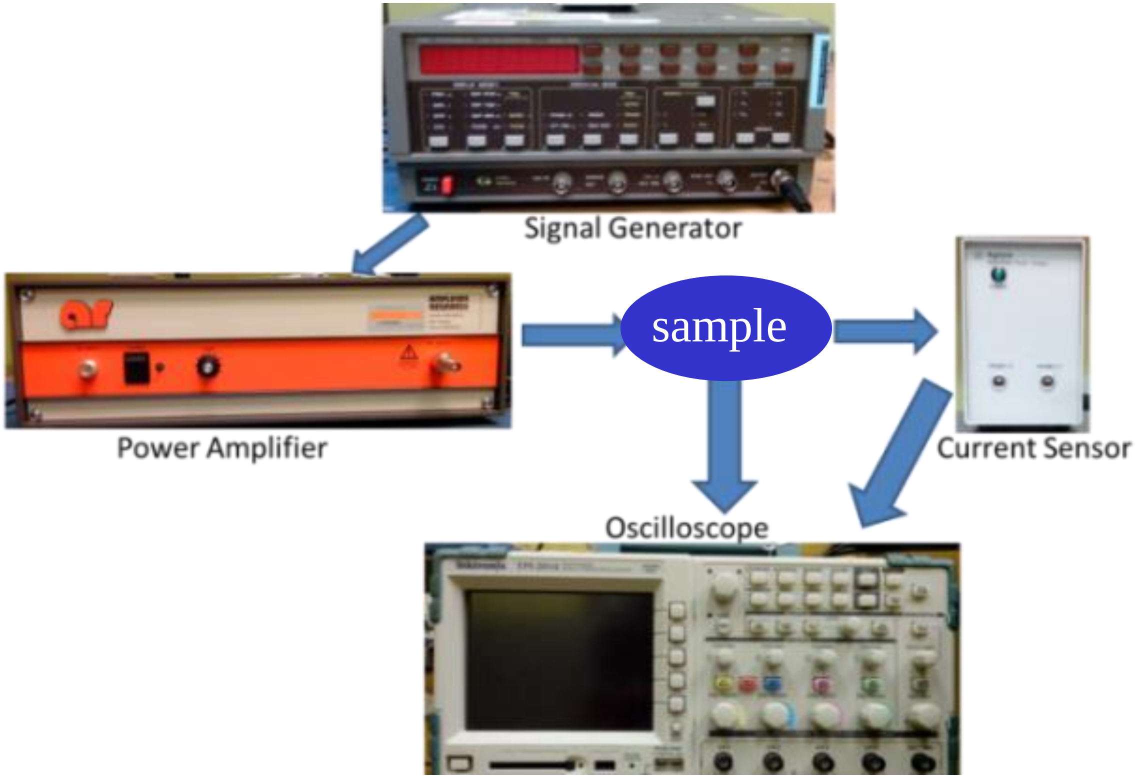
- Commercial magnetic thin film alloys have very high permeability(typically > 20,000)
- Lower skin depth & hence higher eddy current losses at higher frequencies
- Electrodeposited thin films have higher coercive fields (20-80 A/m)
- Presence of crystalline structure in plated NiFe alloys suggests impeding domain wall motion, hence larger coercivity
- Nanocrystalline thin films have ultra-low coercivity (<2 A/m), hence lower losses
- Less impediment for domain wall motion due to absence of magnetocrystalline anisotropy
- However, eddy currents can be further reduced by thinning the nanocrystalline thin films

Review of Soft Magnetic thin films

Materials	Research polycrystalline thin films (NiFe)	Research Amorphous thin films (CoP)	Nanocrystalline thin films (Vitroperm, MT, etc)
Thickness (um)	3~5	3~5	>16
Coercivity (A/m)	20 ~ 80	10-20	<3
Resistivity (Ω.m)	25 ~ 45 $x10^{-8}$	>100 $x10^{-8}$	~110 $x10^{-8}$
Saturation Flux Density (T)	0.8 ~ 1.5	0.8 ~ 1.5	1.2
Relative Permeability	<1000	<1000	>15000

Magnetic Core loss measurement set-up

- Test samples prepared as toroidal transformers
- Current sensor measures primary current (I)
- Oscilloscope measures secondary voltage (U)
- Power loss, P= U.I
- Air-core contribution compensated for accurate core loss measurement

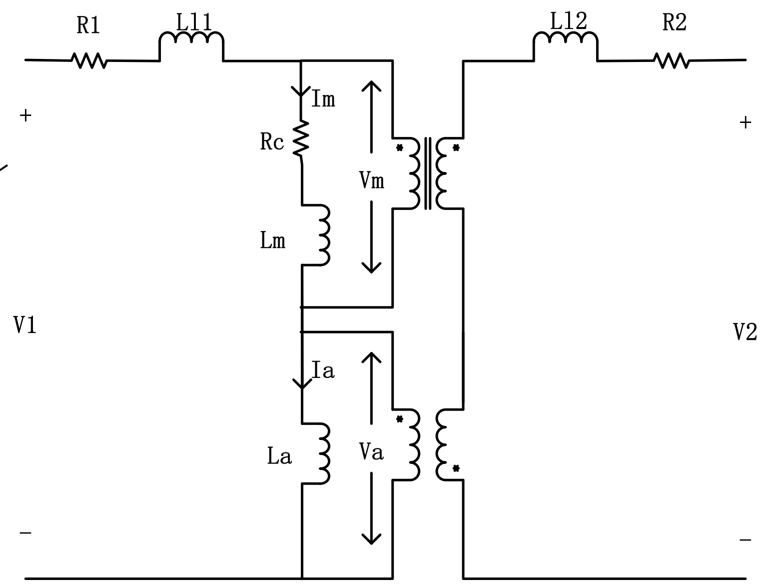


Air-core contribution

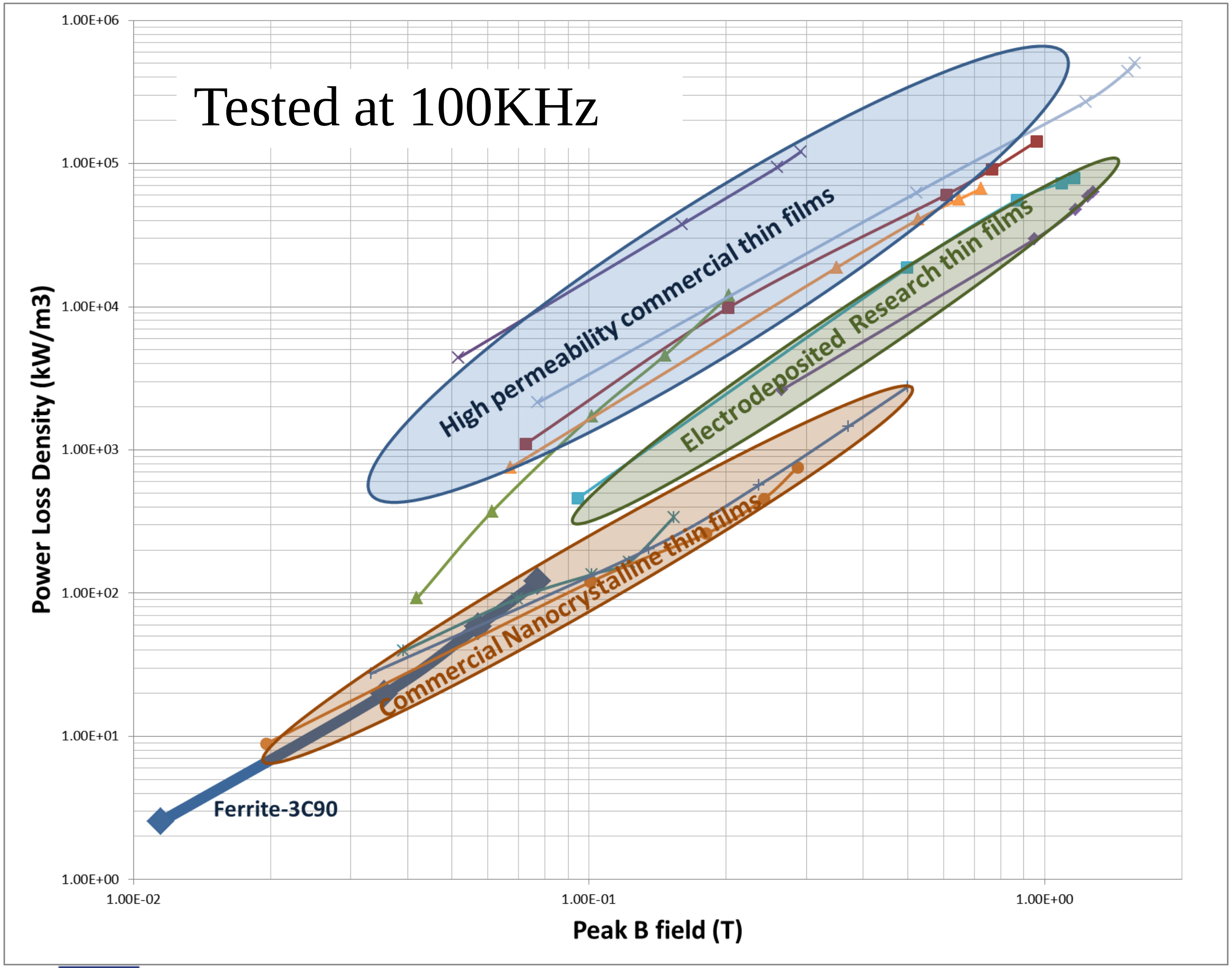
- Air-core contribution eliminated by including air-core transformers in the circuit
- Air-core transformers are similar dimensions to magnetic core test samples
- Air-core transformer is connected in series to primary (same excitation current thru' air-core & magnetic core)
- Another air-core transformer connected with opposite polarity to the secondary (air coupling from magnetic core cancels)

Magnetic core | Air core

$$V = N \cdot A \cdot \frac{dB}{dt} = \boxed{N \cdot Ac \cdot \frac{dBc}{dt}} + \boxed{N \cdot Aa \cdot \frac{dBa}{dt}}$$



Power Loss Densities of Soft Magnetic

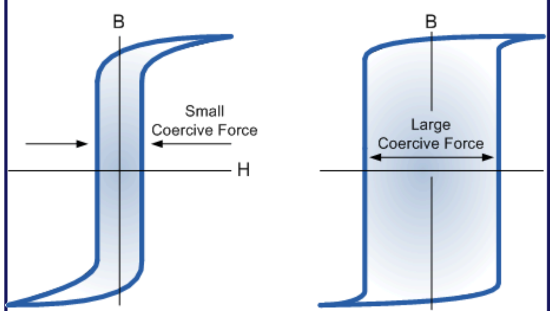


Magnetic Core Losses

- **Magnetic core losses can be broadly classified**

Hysteresis Loss

- Impede domain wall motion
- Loss manifests as Coercive field



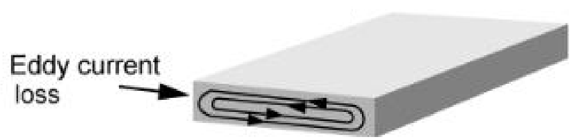
- Higher coercivity → higher hysteresis loss
- Hysteresis loss,

$$P_h = 4 \cdot f \cdot B_{ac}{}^2 \cdot \frac{H_c}{B_{sat}}$$

Eddy Current Loss

-Eddy current resist change in applied magnetic field

-Skin depth, thickness at which the current density drops to 1/e



-Eddy current loss depends on conductivity & permeability of material

-Eddy current loss (thickness less than one skin depth)

$$Pe = \frac{\varpi^2 B_{sat}{}^2 \sigma a^2}{24}$$

Anomalous Loss

-Inconsistencies in domain wall motion during magnetization reversal

-Variations in localized flux densities

- Model for estimating anomalous loss proposed by Bertotti (Book- Hysteresis in Magnetism)

$$P_{excess} = 8\sqrt{dw}\sqrt{\frac{GV_o}{\rho}}(B.f)^{\frac{3}{2}}$$

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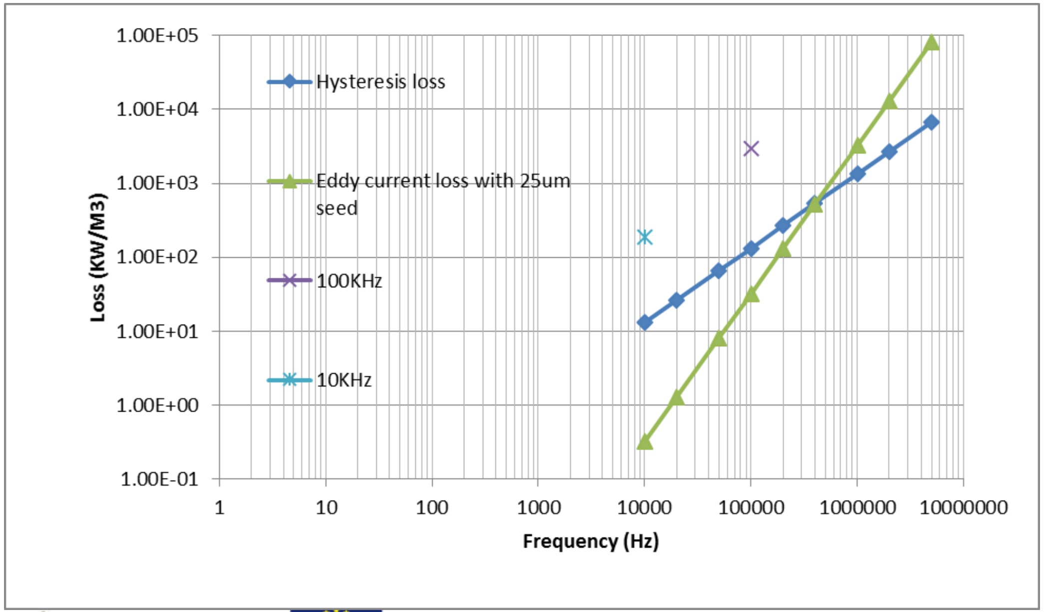
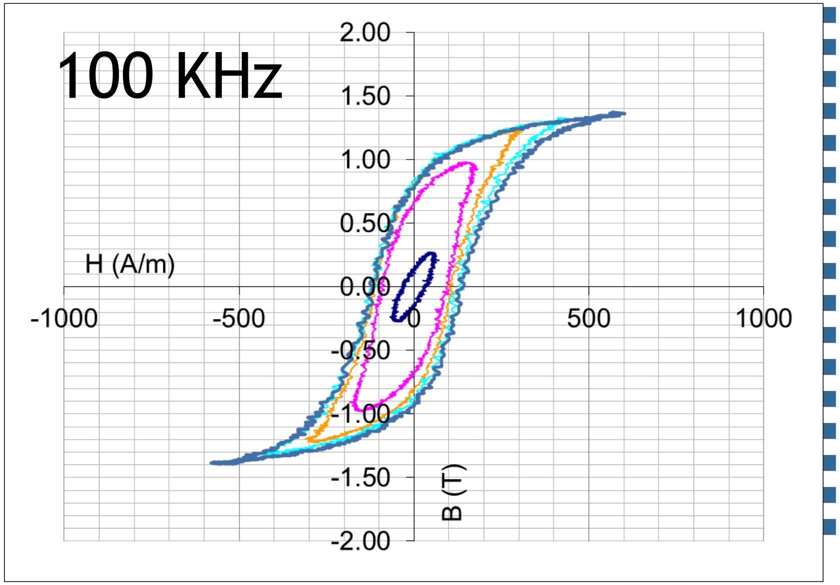
Analysis of Core losses in Polycrystalline thin films - Permalloy

–Test conditions- Frequency- 100 kHz; Bacpeak- 100 mT; thickness- 3 μm

- Classical eddy current loss = 32.4 kW/m^3; 1.1% of total loss,
- Hysteresis loss = 1333 kW/m^3; 45% of total loss
- Anomalous loss = 1624 kW/m^3; **53.9% of total loss**

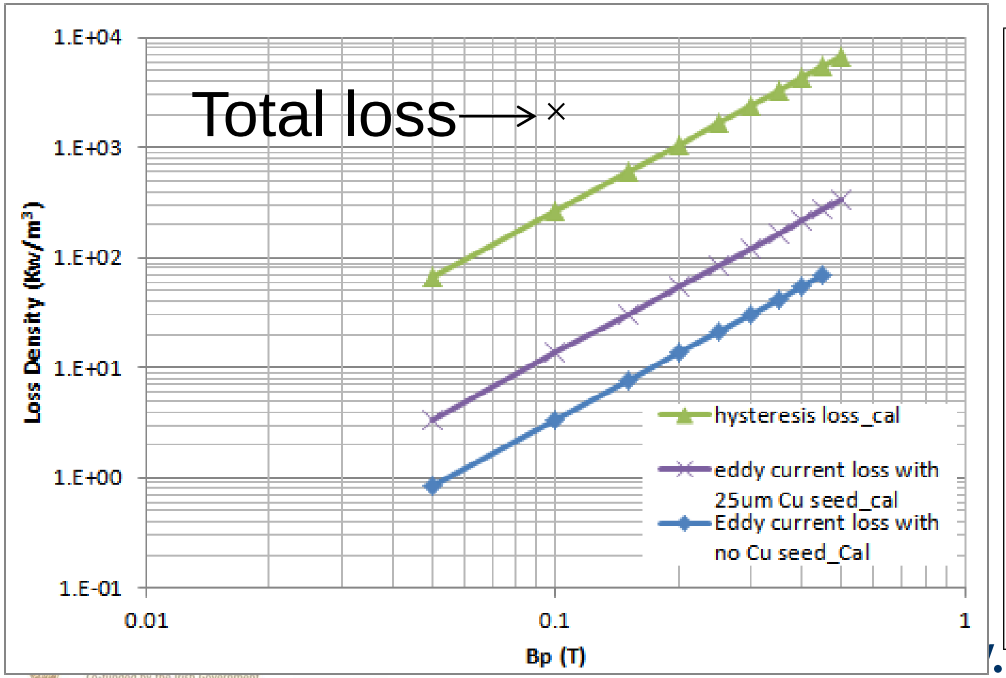


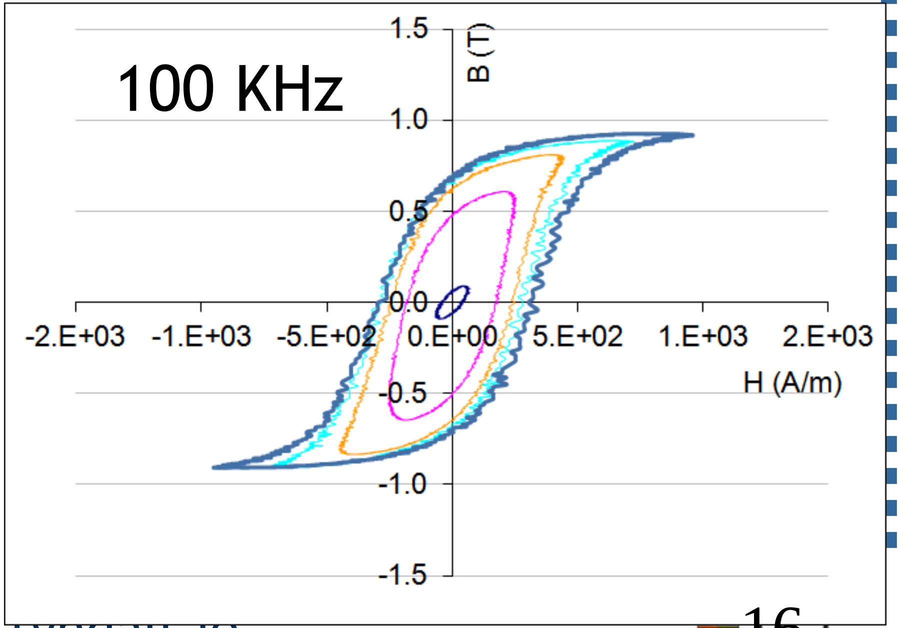


Analysis of Core losses in Amorphous soft magnetic thin films- CoP

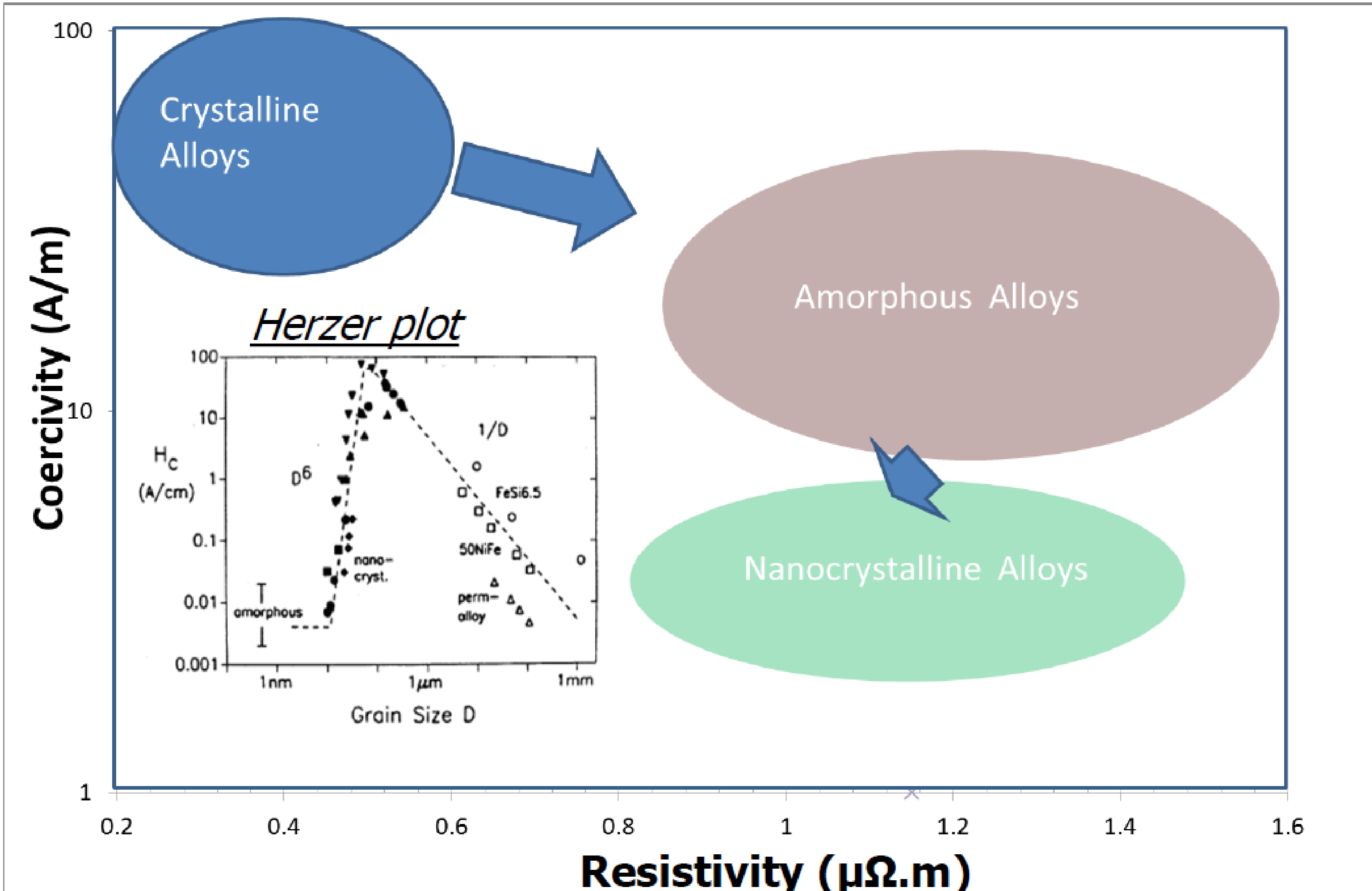
-Test conditions- Frequency- 100 kHz; Bacpeak- 100 mT; thickness- 3 μm

- Classical eddy current loss = 4.5 kW/m^3; 0.2% of total loss,
- Hysteresis loss = 116.6 kW/m^3; 5.8% of total loss
- Anomalous loss = 1879 kW/m^3; **94% of total loss**



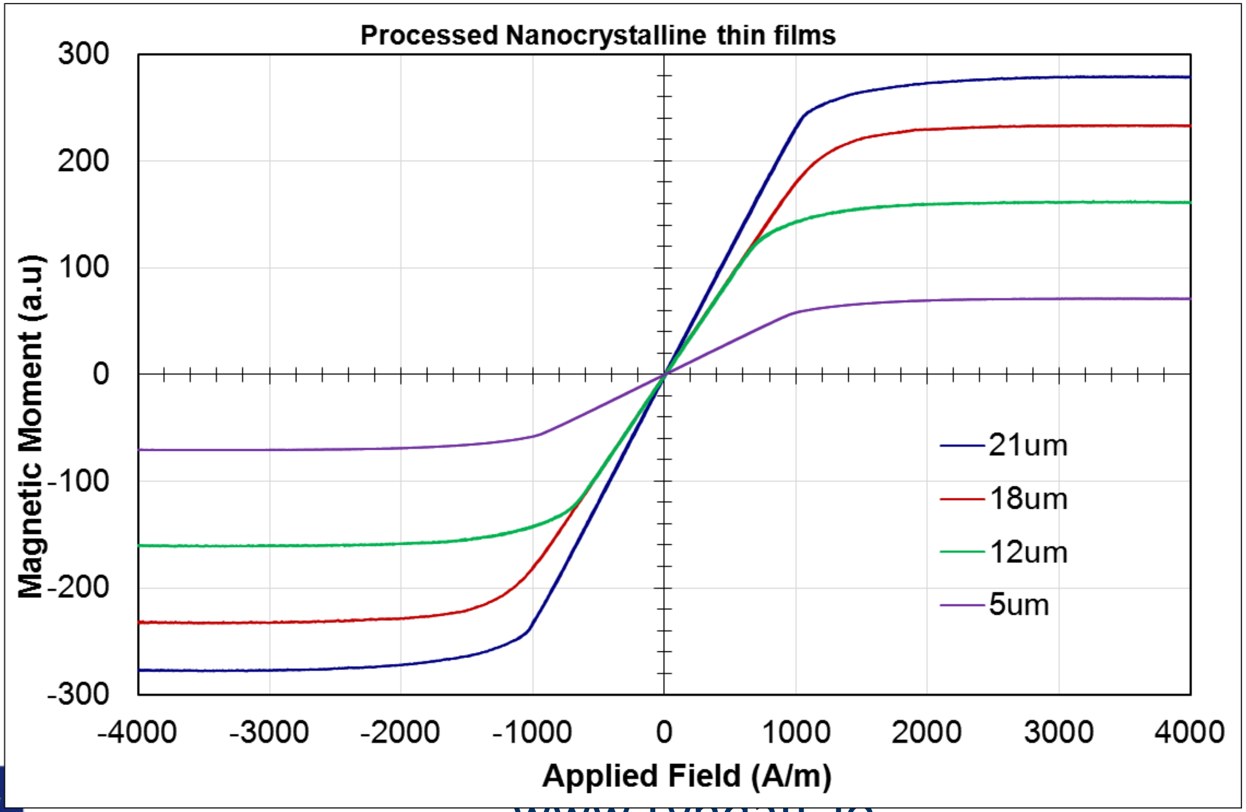


Summary of Magnetic thin film review



Post Processed Commercial Nanocrystalline thin films

- Thinning of nanocrystalline material required for reducing eddy current losses
- Chemical etching technique using dilute Nitric acid for thinning
- BH loop measurements done using SHB instruments BH loop tracer
- Pre-etch thickness- 21 µm, material thinned to 18 µm, 12 µm & 5 µm thicknesses
- Coercivity for all thicknesses remains the same, suggesting no change in hysteresis loss

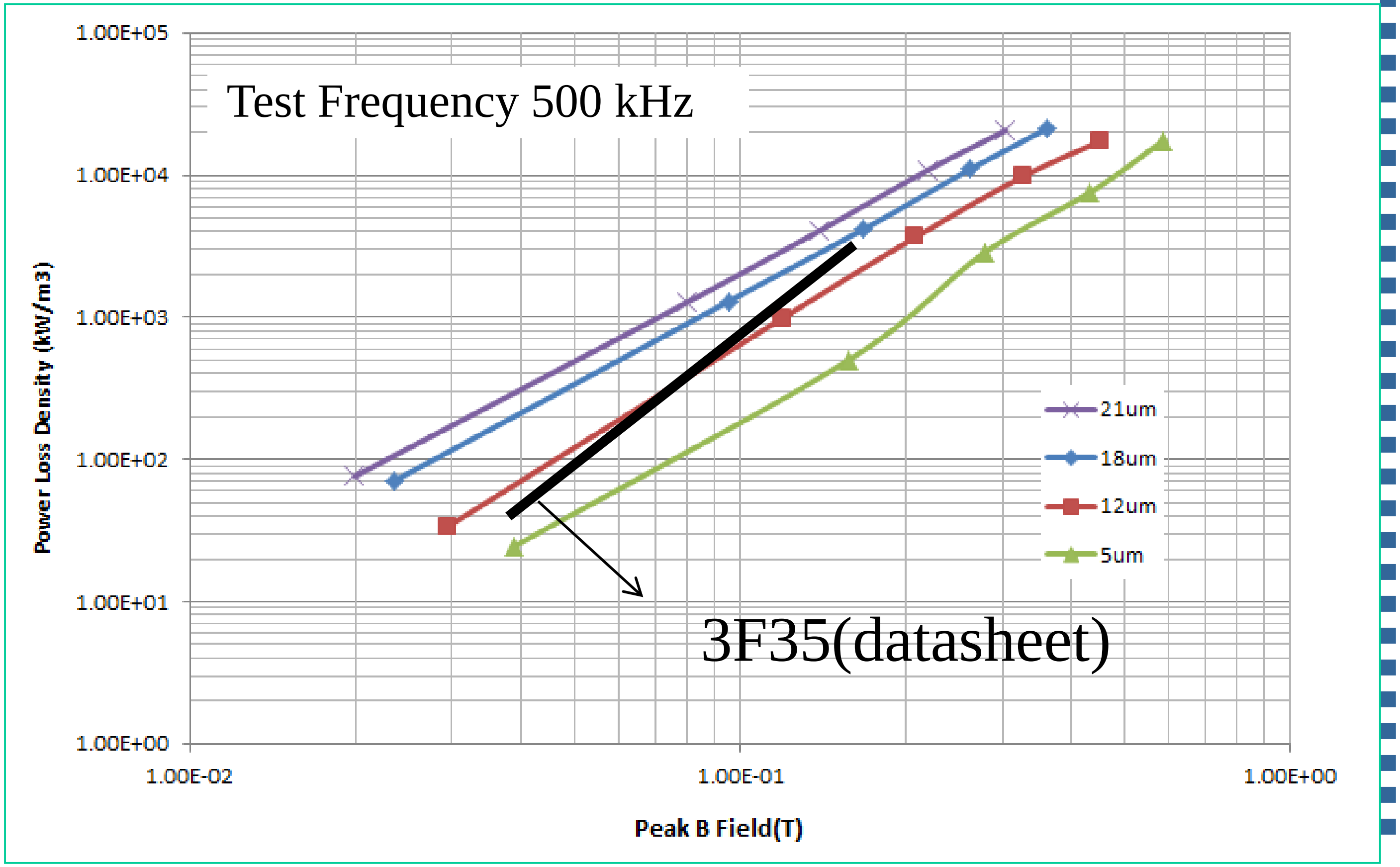


Measurement & Discussion

- Post processed thin films assembled into toroidal cores with OD- 7.7 mm & ID- 7.5 mm
- Toroidal cores arranged as transformers with 25 turn Cu windings (1:1)
- Similar air-core transformer for air core compensation

Magnetic Core

Air-Core

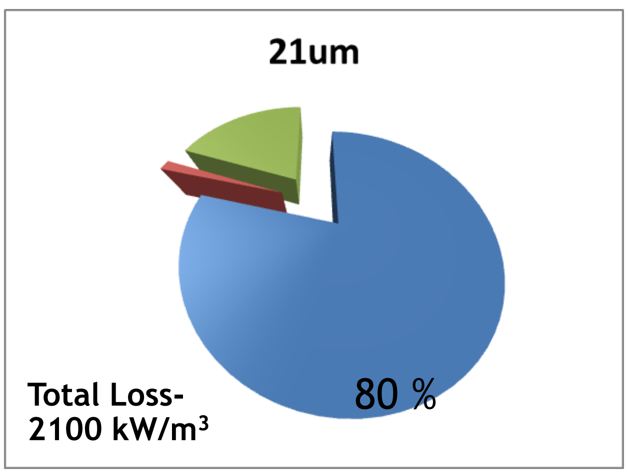


Measurement Results

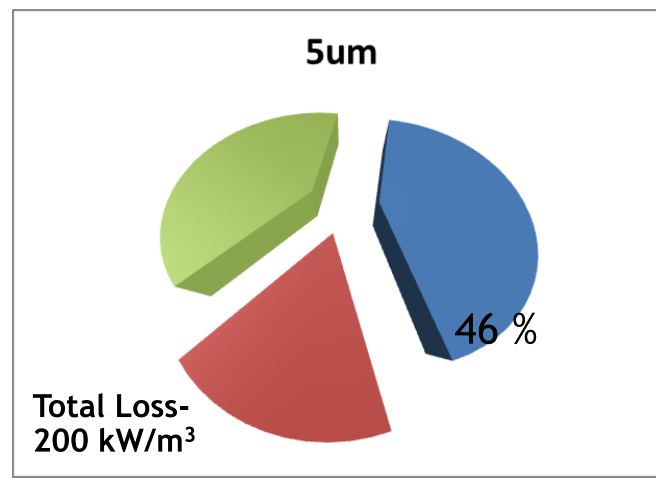
Losses	21 µm	5 µm
Eddy Current	1650 kW/m^3	93 kW/m^3
Hysteresis	31 kW/m^3	31 kW/m^3
Anomalous	419 kW/m^3	76 kW/m^3

$$Pe = \frac{\varpi^2 B_{sat}{}^2 \sigma a^2}{24}$$

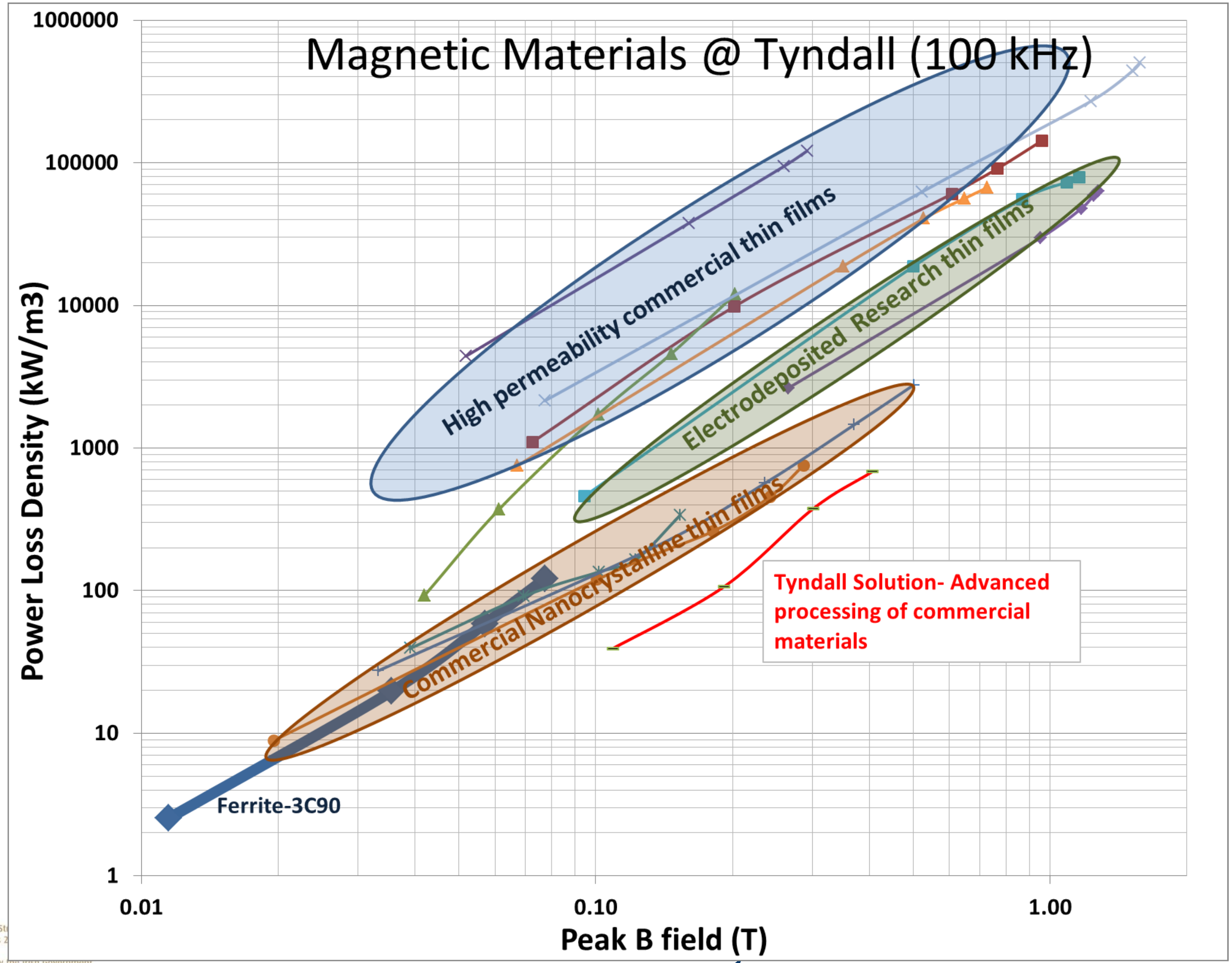
$$P_h = 4 \cdot f \cdot B_{ac}{}^2 \cdot \frac{H_c}{B_{sat}}$$



Eddy current
Anomalous
Hysteresis

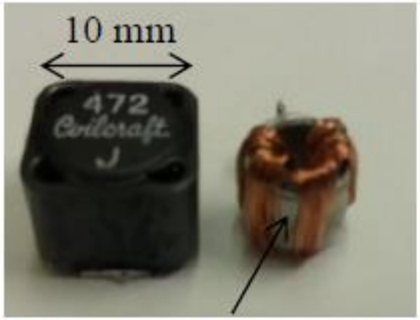


Material performance comparison



Potential Impact on magnetic components

- Lower loss density ➡ higher efficiency
  ➡ smaller core size
  ➡ shorter conductor length
  ➡ higher power density
- Higher B_{sat} ➡ Greater design flexibility



Tyndall Inductor

☑ ***40% reduction in device volume***

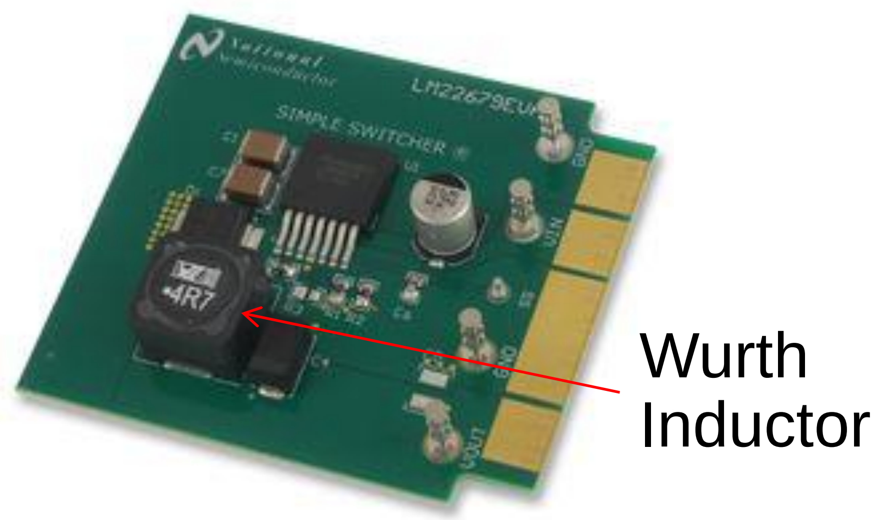
☑ ***25% reduction in magnetic loss***

Ferrite chip inductor vs Post processed thin film core inductor

- *AN-1891 LM22679 Evaluation Board (TI)*

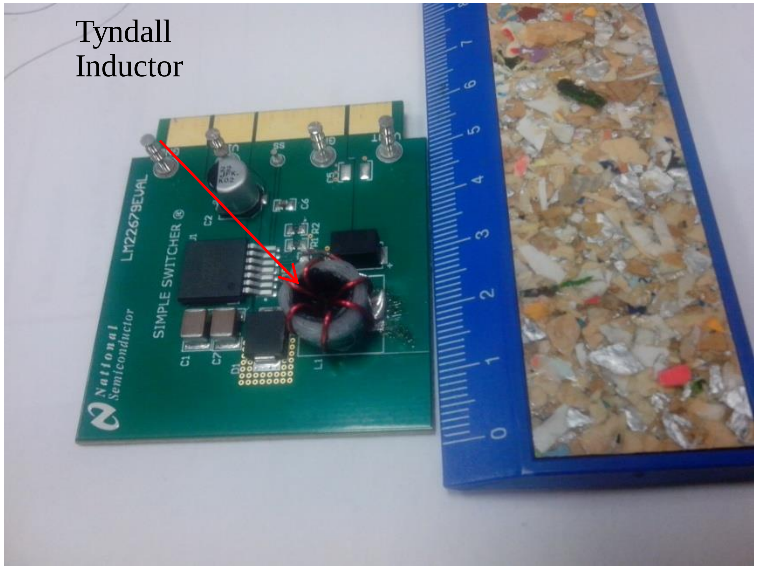
The performance of the evaluation board is as follows:

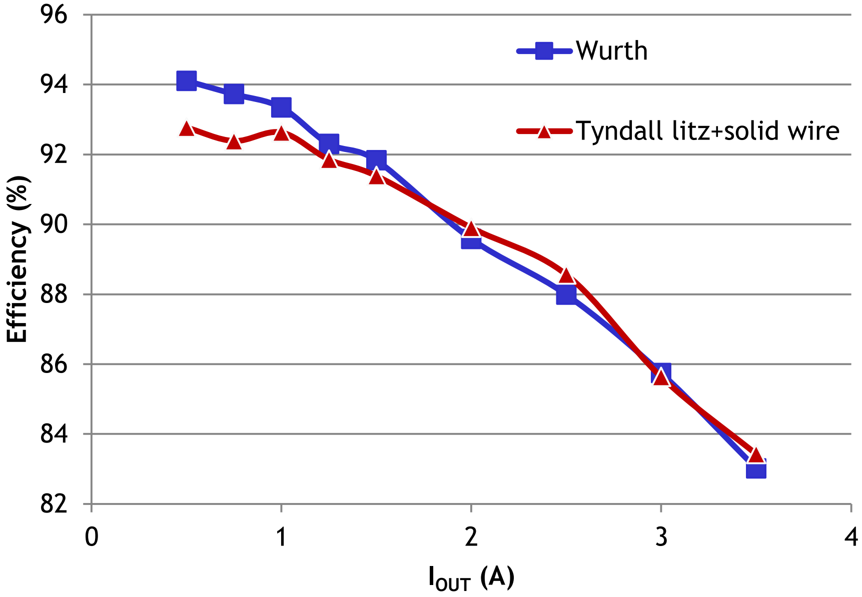
- Input Range: 4.5V to 42V
- Output Voltage: 3.3V
- Output Current Range: 0A to 5A
- Frequency of Operation: 500 kHz
- Board Size: 2.25 × 2 inches (57 mm ×
- Package: TO-263 THIN
- Inductance required- 4.7 µH
- Discrete Inductor on board- Wurth Elektronik- SMD- 74477004



Performance evaluation- Tyndall vs Wurth

LM22679 Evaluation Board





- Input Voltage : 5 V
- Output Voltage: 3.3V
- Output Current Range: 1 A to 3.5 A
- Frequency of Operation: 500 kHz

Wurth inductor:

-4.8 µH

-DCR 12mΩ

Tyndall gapped inductor:

-4.7 µH

-DCR 15 mΩ

-Efficiency the same at currents > 2 A

Conclusions

- Post processing nanocrystalline thin film material is demonstrated
- Processed material characterized; compared to Ferrite & other thin film materials
- Very low loss density achieved using post-processing of nanocrystalline thin film material:
  - 200 kW/m^3 @500kHz & 0.1T Bpeak vs. **700 kW/m^3** for 3F35
  - 30 kW/m^3 @ 100kHz & 0.1T Bpeak vs. **70 kW/m^3** for 3C90
- Demonstrated performance of post-processed nanocrystalline thin film material
  - 40% reduction in device volume
  - 25% reduction in magnetic loss

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Key publications

- S. Kulkarni, D. Li, N. Wang, S. Roy, C. Ó Mathúna, G. Young, P. McCloskey, "Low loss Magnetic thin films for off-line power supplies", IEEE Transactions on Magnetics, 50, 1-4, (2014)
- S. Kulkarni, N. Wang, Z. Pavlovic, D. Li, P. McCloskey,G. Young, C. Ó Mathúna, "Low Loss Thin Film Magnetics for High Frequency Power Supplies", Proceedings of 16th European Conference on Power Electronics and Applications (EPE'14-ECCE EUROPE), Lappeenranta, Finland 2014.