Magnetic Nanocomposites for Inductive Components in Power Electronics.

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Target Opportunities.

http://www.nist.gov/pml/high_megawatt/

Recent Cost Models (Al Hefner, SECA) for power electronics indicate substantial cost savings for medium and high voltage inverter circuits.

Power electronic devices require power conditioning using HF transformers, inductive filters and other inductive components.

Nanocomposite magnetic materials offer significant advantage over Si steels at higher frequencies because of their high resistivities and thin cross-section.

HITPERM nanocomposite magnetic materials offer significant advantage over ferrites because of their large inductions and field tuneable permeabilities.

HITPERM nanocomposite magnetic materials have robust high T properties and High frequency performance superior to FINEMET.

CMU – Alloy Development
Magnetics – Core Development
LANL – Transformer Design, Construction
NETL – Energy Applications

$P_L \sim B^2 f^n t/\rho$

$n \sim 1\text{-}2$

High Frequency Nanocrystalline Transformers Are Over 150 Times Lighter And Significantly Smaller (At Same Power)

HVCM Transformer

- 150 kV, 20 KHz
- 20 Amp RMS
- 1 MW Average (3) Present Use
- 450 LBS for 3
- 3 KW Loss At 2 MW
- “C” Core Design (Parallel Windings)

Typical H.V. Transformers

- 100 kV, 60 Hz
- 20 Amp RMS
- 2 MW Average
- 35 Tons
- ~30 KW Loss

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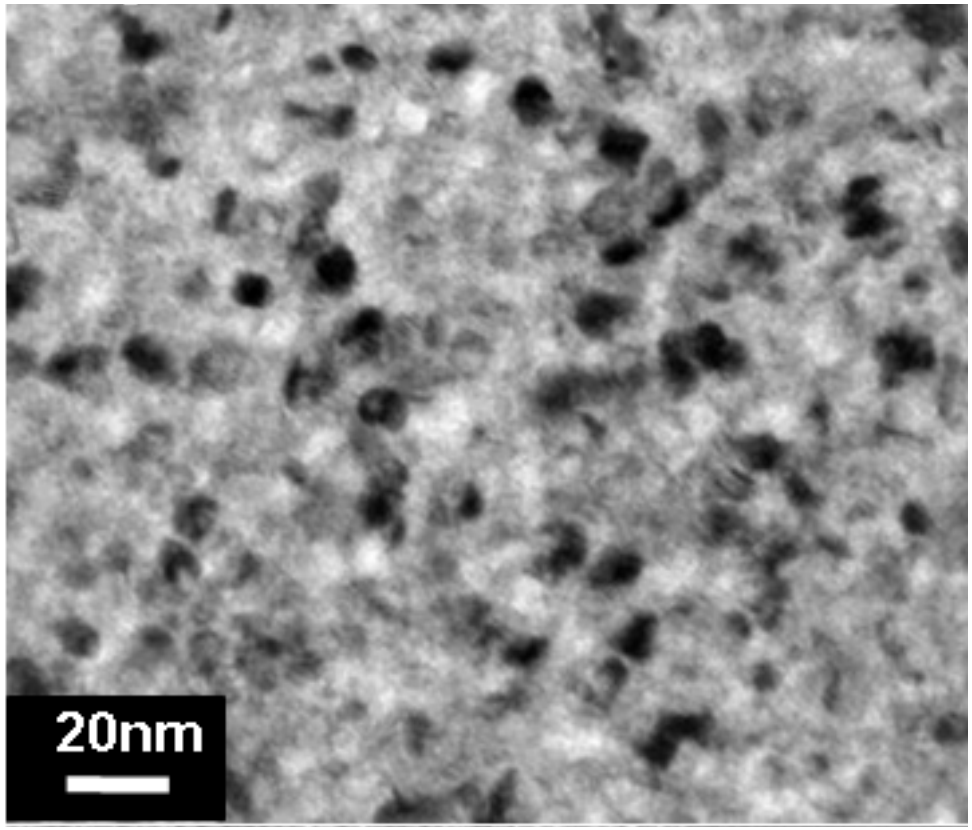
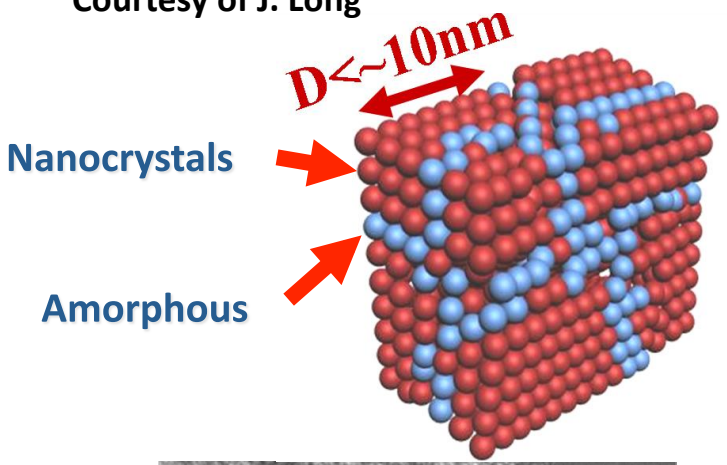
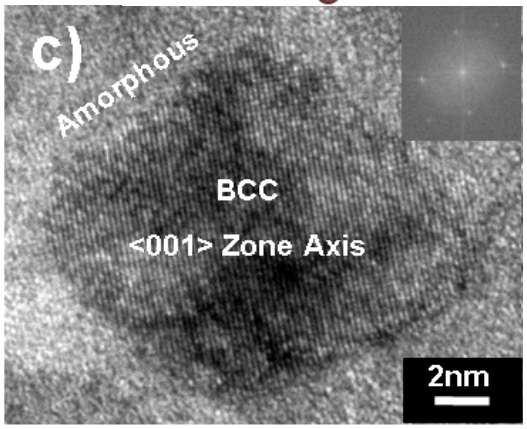
What are Nanocomposites?



Courtesy of J. Long

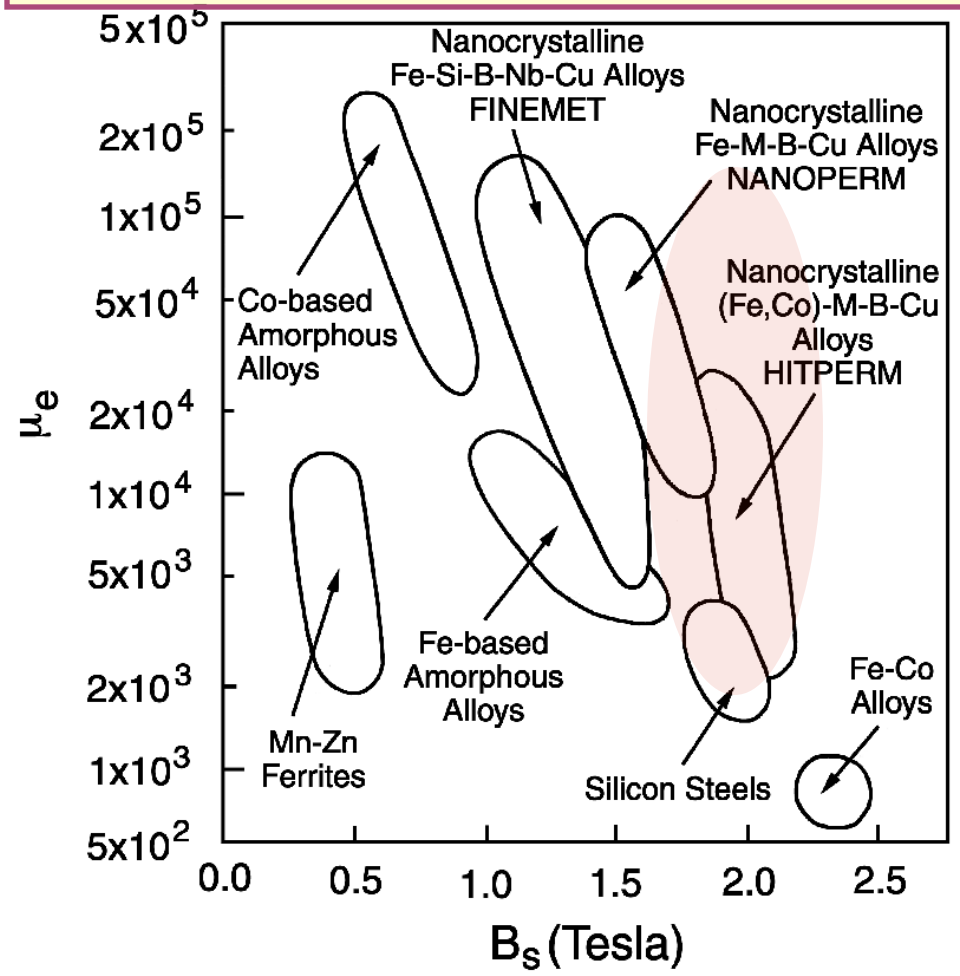


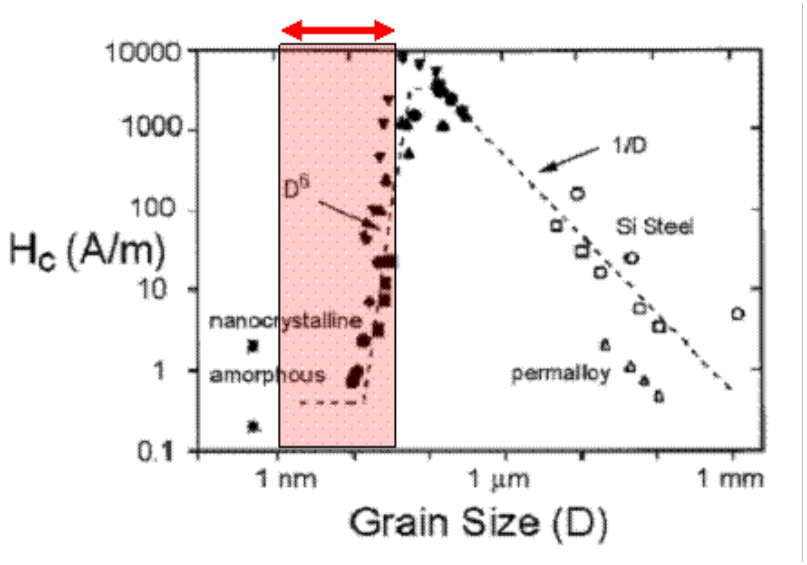


Ferromagnetic Nanocrystals Embedded in an Amorphous Matrix:

Nanocrystals → Desired Magnetic Properties
Amorphous Phase → Small Grain Size and Large Resistivity

Materials Choices: Permeability, Induction and Curie Temperature



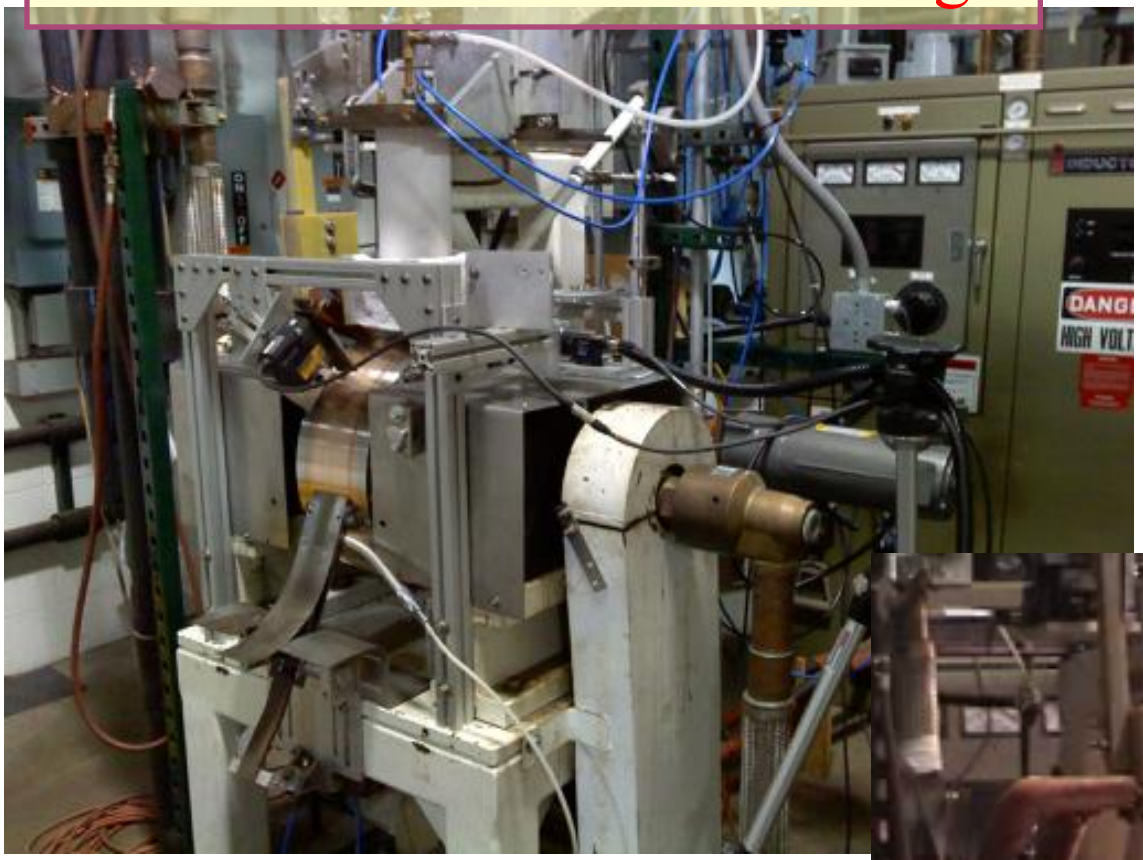


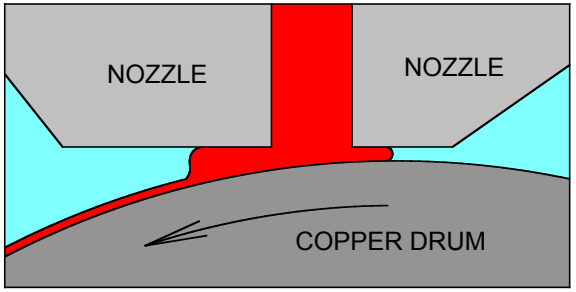
Alloy Name	Typical Composition	Nanocrystalline Phase	B_S	T_c
FINEMET	$Fe_{73.5}Si_{13.5}B_9Nb_3Cu_1$	α-FeSi, FeSi (DO_3)	1.0 – 1.2 T	< 770 ^{0}C
NANOPERM	$Fe_{88}Zr_7B_4Cu$	α-Fe (BCC)	1.5 - 1.8 T	770 ^{0}C
HITPERM	$Fe_{44}Co_{44}Zr_7B_4Cu$	α, α'-FeCo, (BCC,B2)	1.6 – 2.1 T	> 965 ^{0}C

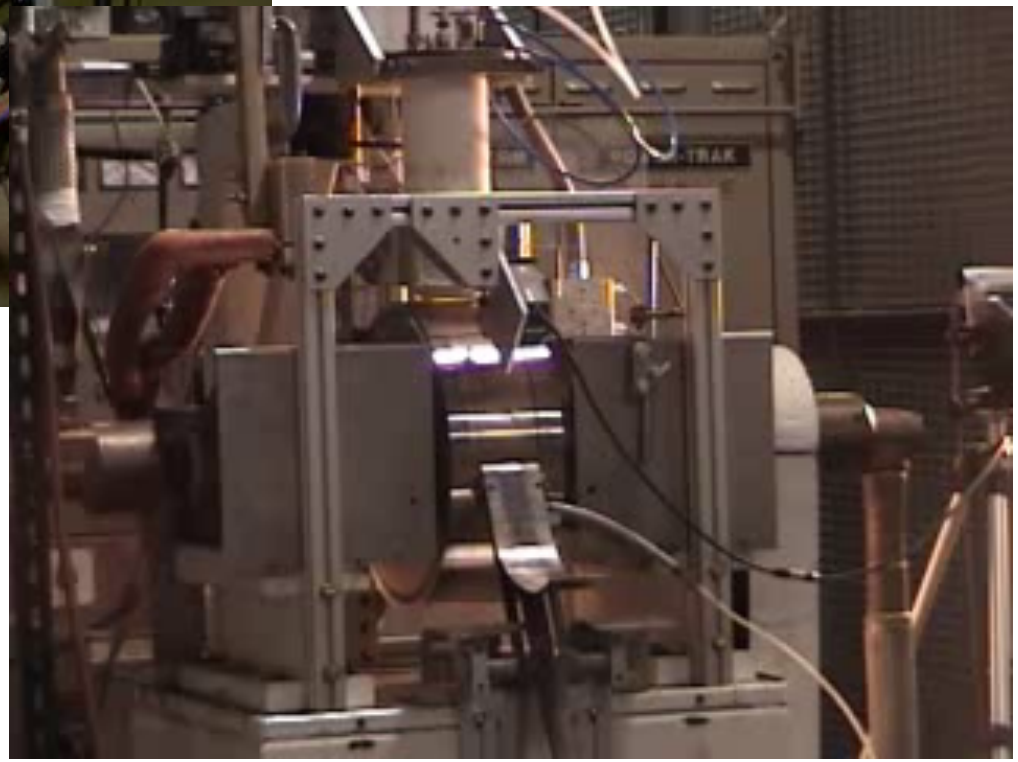
Frequency Response:

Resistivity
Lamination
Thickness

Lab Scale Planar Flow Casting.







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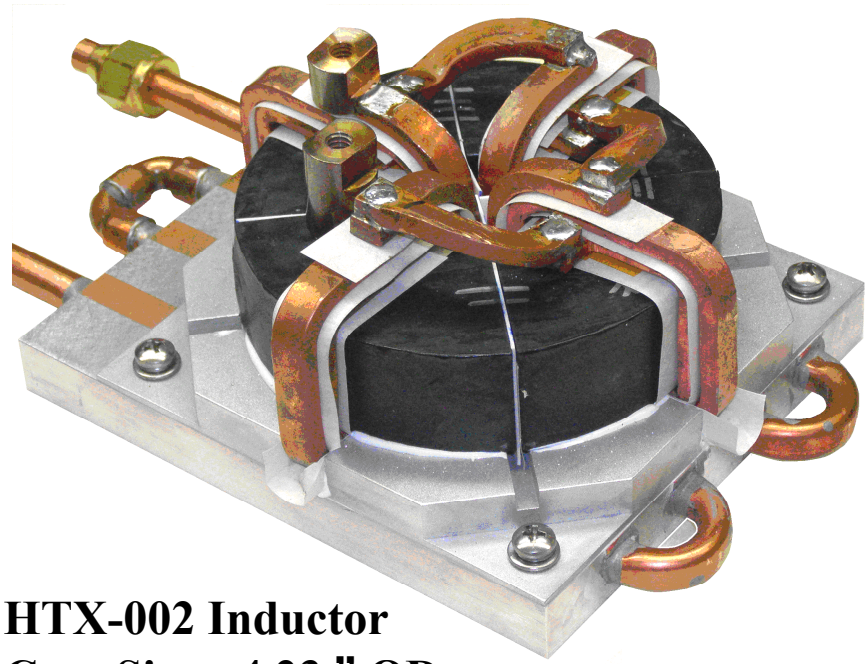
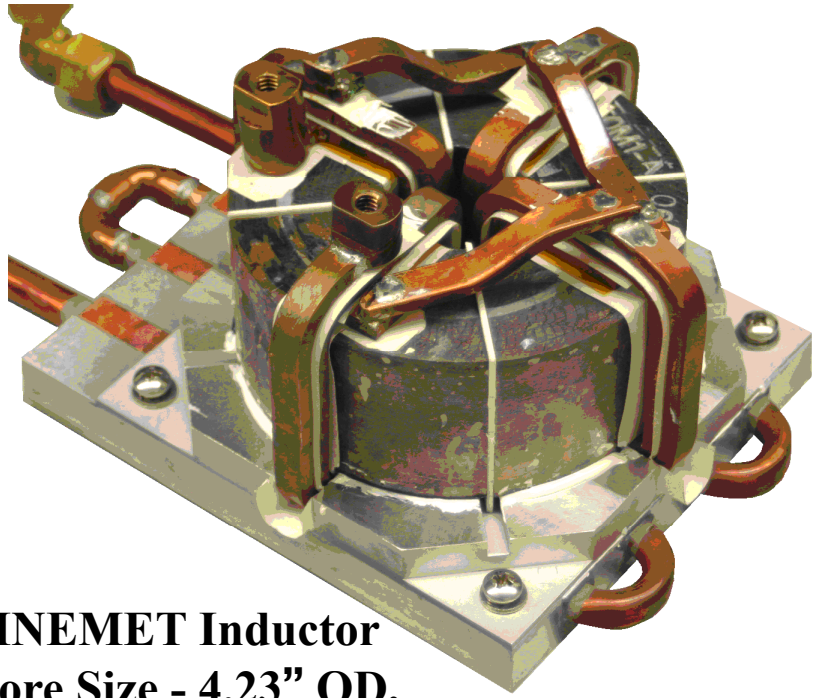
Results: New high-Bs, high-T_c nanocomposite, with nanocrystals with a FeCo A2 or B2 structure embedded in an amorphous matrix for high-power inductors.

FOM:

1. Linear *B-H* response μ_r ~1400, constant to H = 1.2 T.
2. Material was used in a 25 μH inductor for a 25 kW DC-DC converter rated for use in discontinuous conduction mode at 300 A peak current and 20 kHz switching frequency.
3. Compared to commercially available materials this new alloy can operate at higher flux densities and higher T's thus reducing the overall size of the inductor.

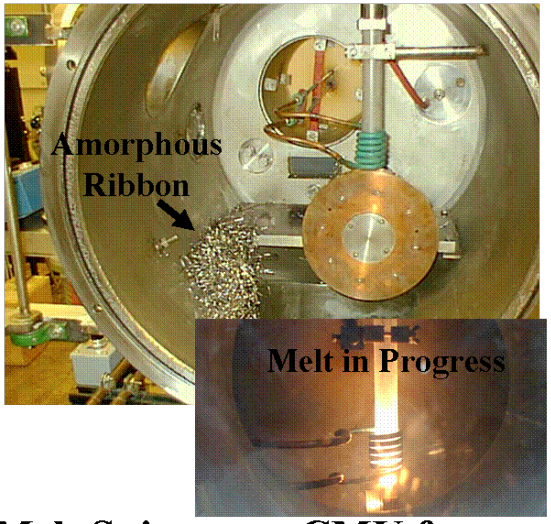


HTX-002 Inductor
Core Size - 4.23 ” OD,
1.325 ” ID, 1.095 ” HT

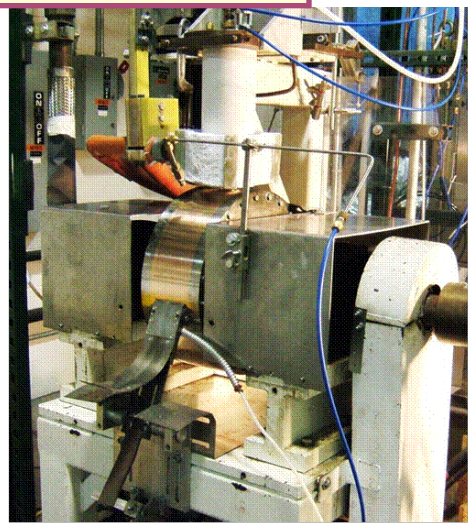


FINEMET Inductor
Core Size - 4.23” OD,
1.325” ID, 1.767” HT

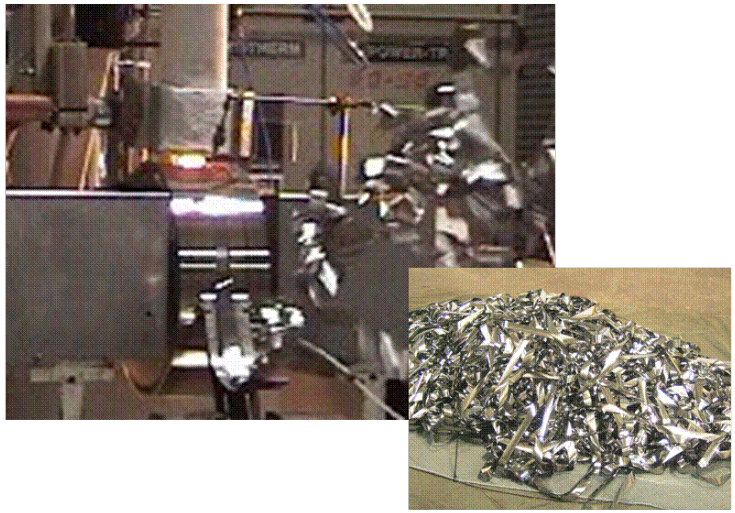
Melt Spinning Processing



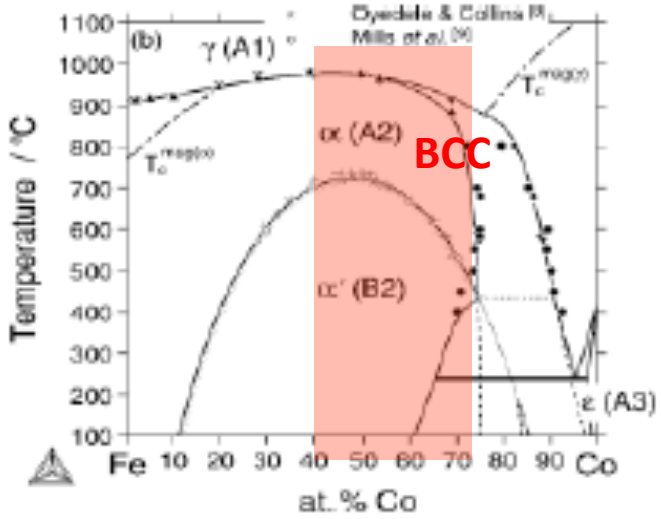
Melt Spinner at CMU for Early Stage Alloy Design and "Proof of Concept"



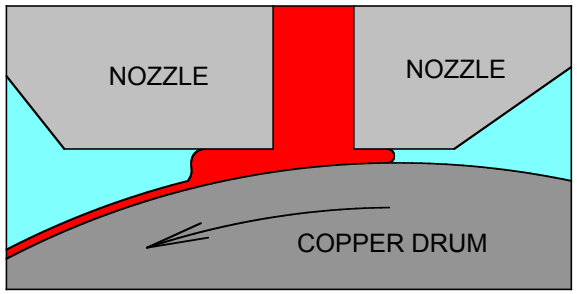
Planar Flow Caster at Magnetics for "Scaled up" Prototypes for Testing



"Miles" of Amorphous Ribbon Obtained From Magnetics Planar Flow Cast



HITPERM Materials
BCC nanox'tals
Large B_s
High T_C
Large K_u



Production Caster

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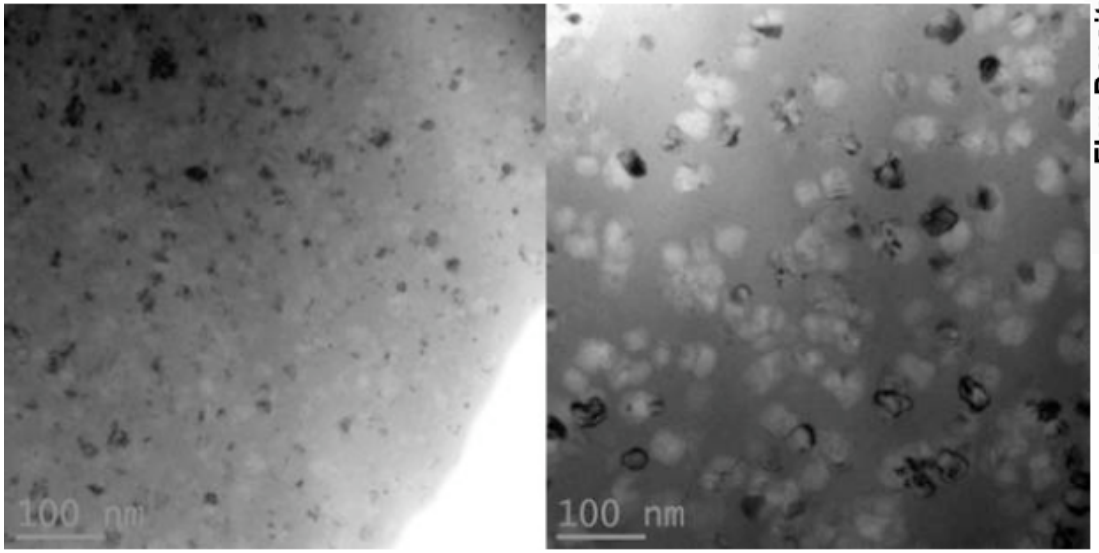
High Induction Materials for ARL Power Transformer

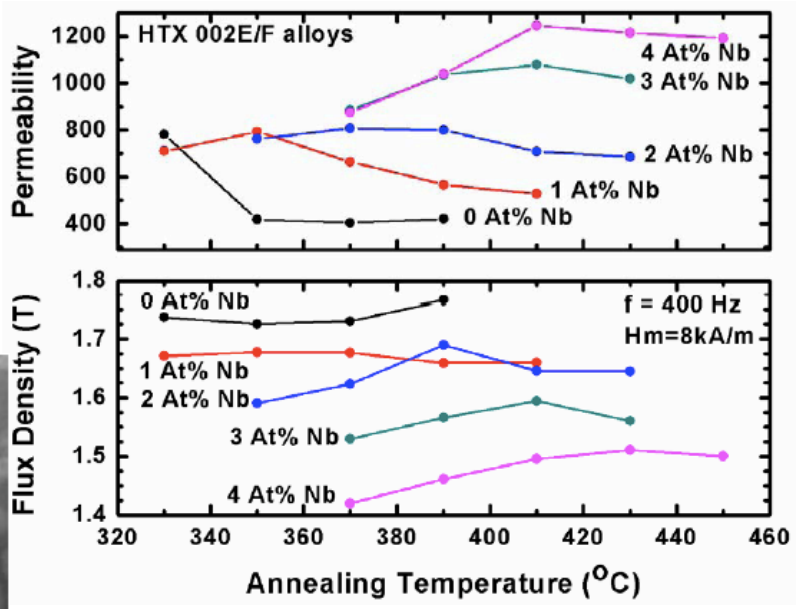
HTX002: $(Fe_{65}Co_{35})_{80+x}B_{13}Nb_{4-x}Si_2Cu_1$

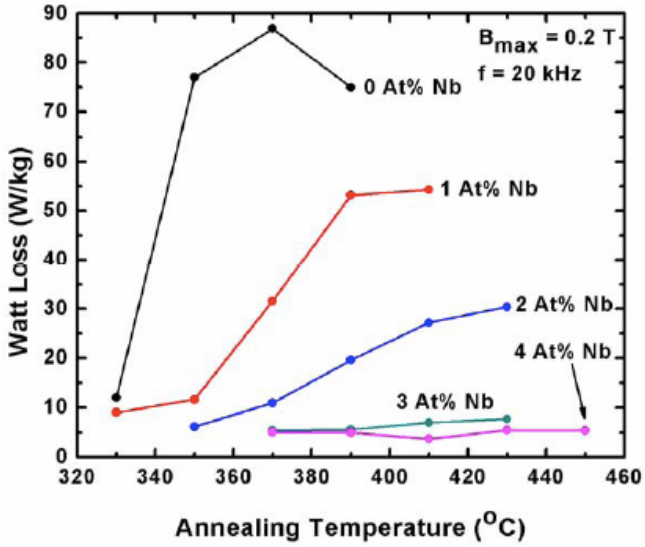
- Ideal Fe:Co ratio of 65:35 found
- Nb-content reduced to increase induction
- 1 at% Nb alloy demonstarted low losses and high saturation induction



4 at% Nb

1 at% Nb





Why is High K_U Technologically Relevant?

Power Electronics: Energy Storage and Conversion… Inductor Applications

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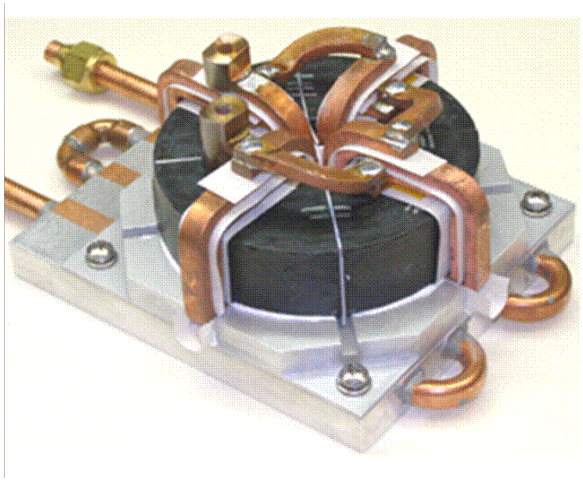
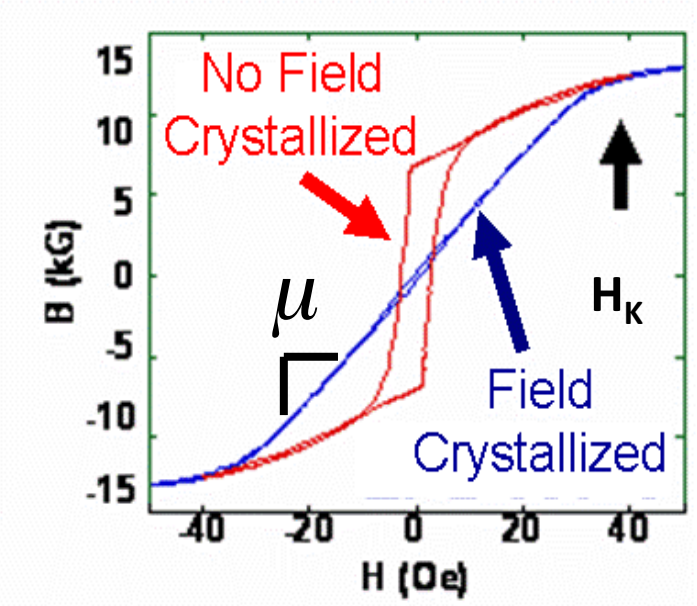


Cut Core Power Transformer



1) **Inductance**

Nonlinear B(H)

DC Bias Problems

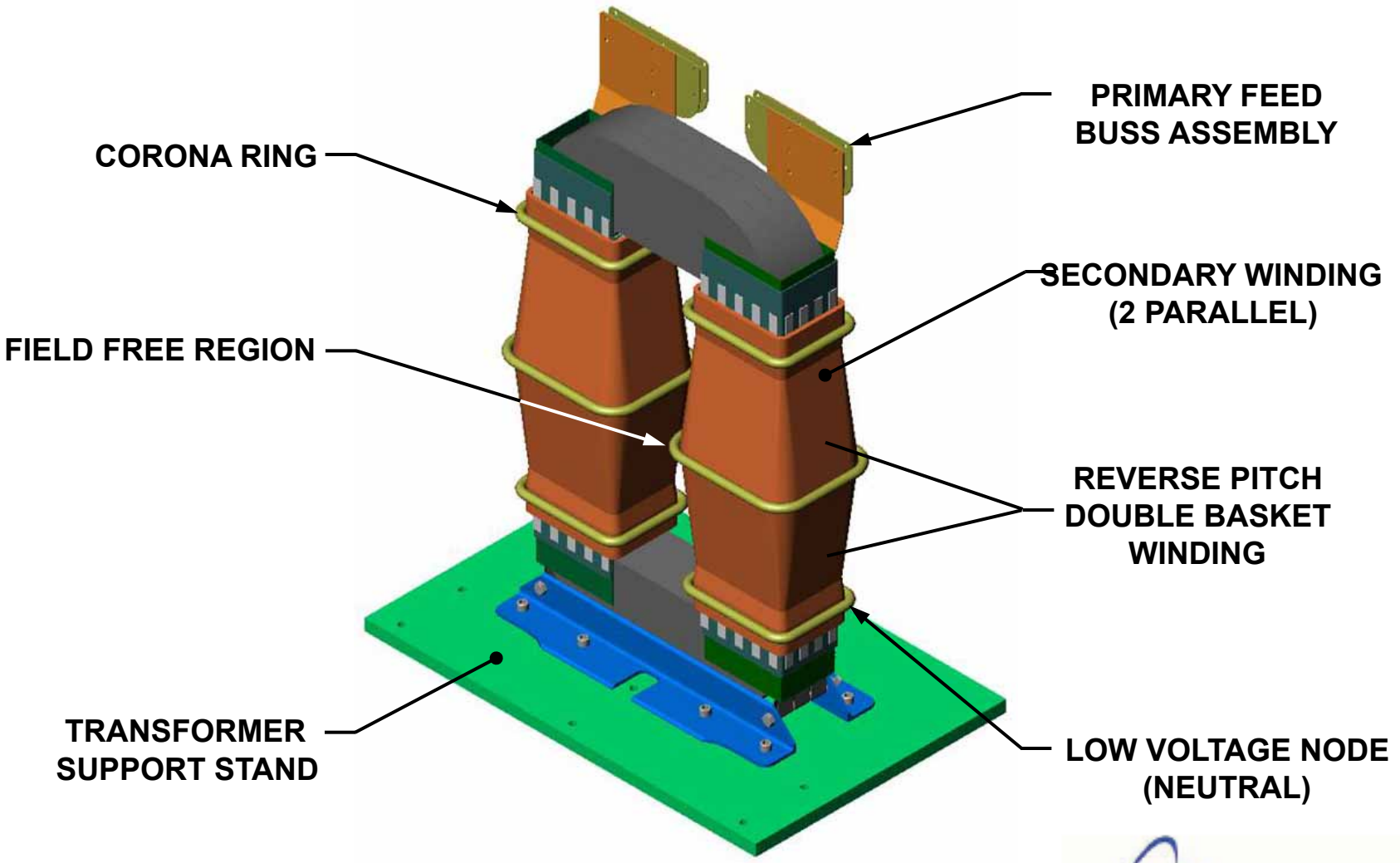
$$L = \mu\left(\frac{N^2 A}{L}\right) \qquad \mu = \frac{dB}{dH}$$

2) **Higher K_U, Lower μ**

Higher Stored Energy

$$E_{Stored} = V_{Core}\left(\frac{B^2}{2\mu}\right)$$

C-core Design, Graded Permeability –Higher Efficiency



Advanced Winding Topology Minimizes Field Stresses And Leakage Inductance

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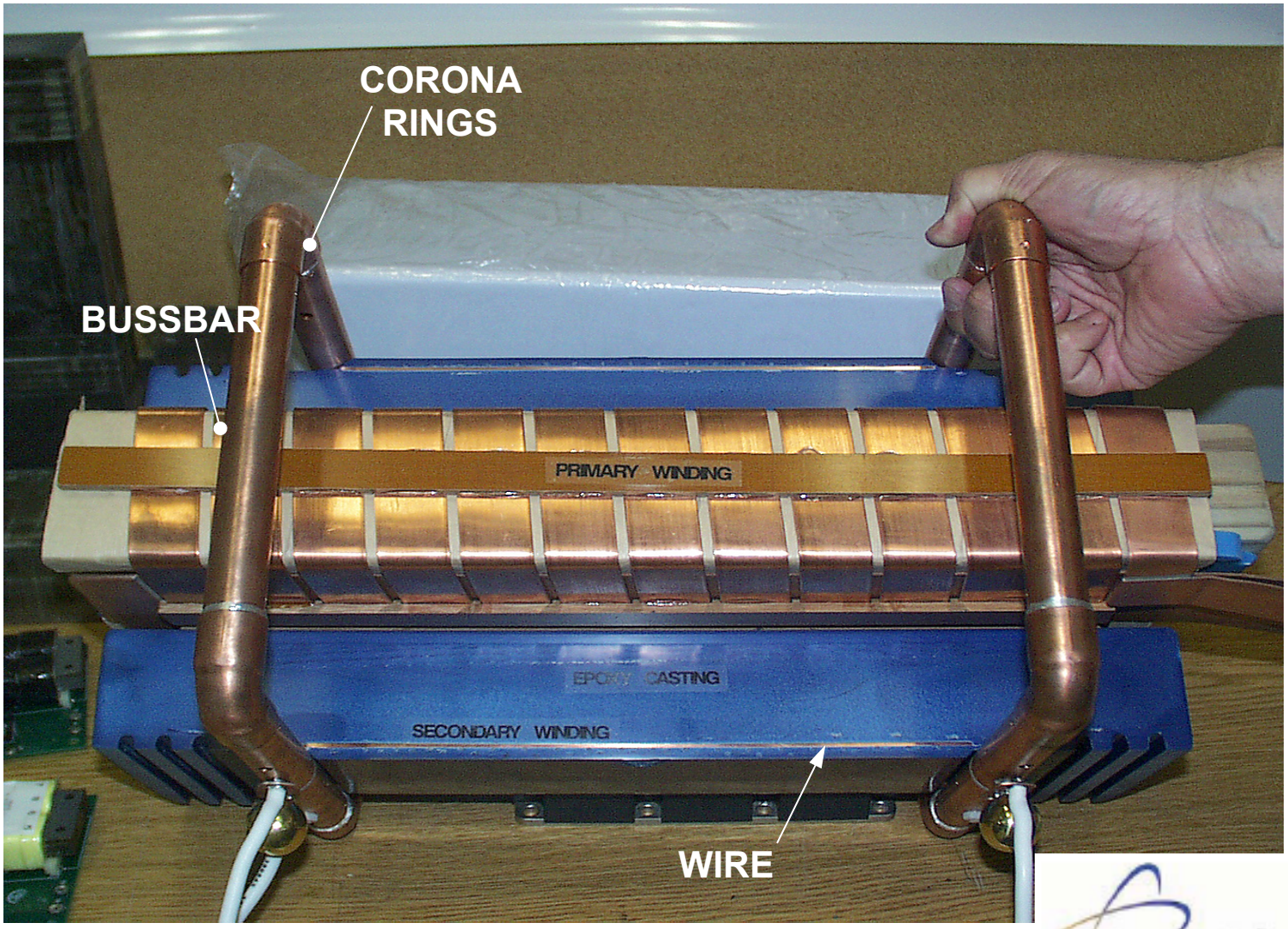
Boost Transformer Windings



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Alloy Comparison

Alloy	Remarks	Applied field	Bm, T	μ	Kr	P0.2/20, W/kg	P0.1/100, mW/cc	Tmax, °C	λs, ppm
HTX 002	Nanocrystalline	TMF	1.47	1500	0.02-0.03	4-6	150	250	20
C	Amorphous	TMF	0.94	670	0.01	5	150		~0
	Nanocrystalline	TMF	0.88	480	0.01	8	230	400	1.4
F	Nanocrystalline	TMF	0.82	220	0.01	6-8	150-200		0.3
A	Amorphous	No field	1.50	1k to 3k*	0.05-0.15*	3-5	70-90		22
D	Nanocrystalline	TMF	1.20	9k to 18k*	0.02-0.04*	1.5	35-45		~0
2605SA1	Amorphous	No field	1.56	1k to 5k*	0.10-0.20*	10	120	155	25
FT-3	Nanocrystalline	TMF	1.25	15k to 20k*	0.04-0.08*	2	60-70	125	~0

* - depend on annealing conditions

Annealing conditions were optimized to get flat B-H loop and minimal watt loss.

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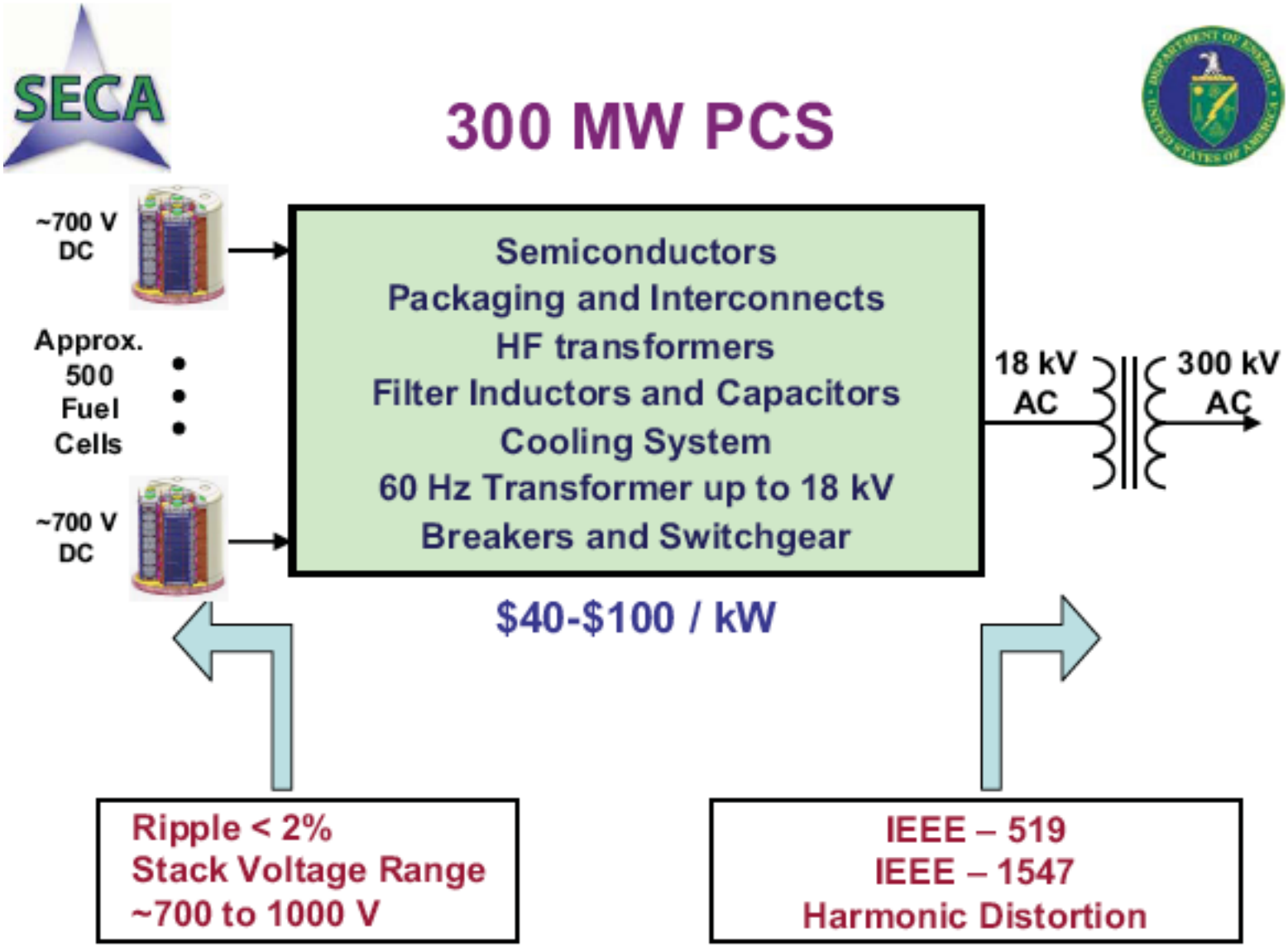
Al Hefner – High MW Proceedings



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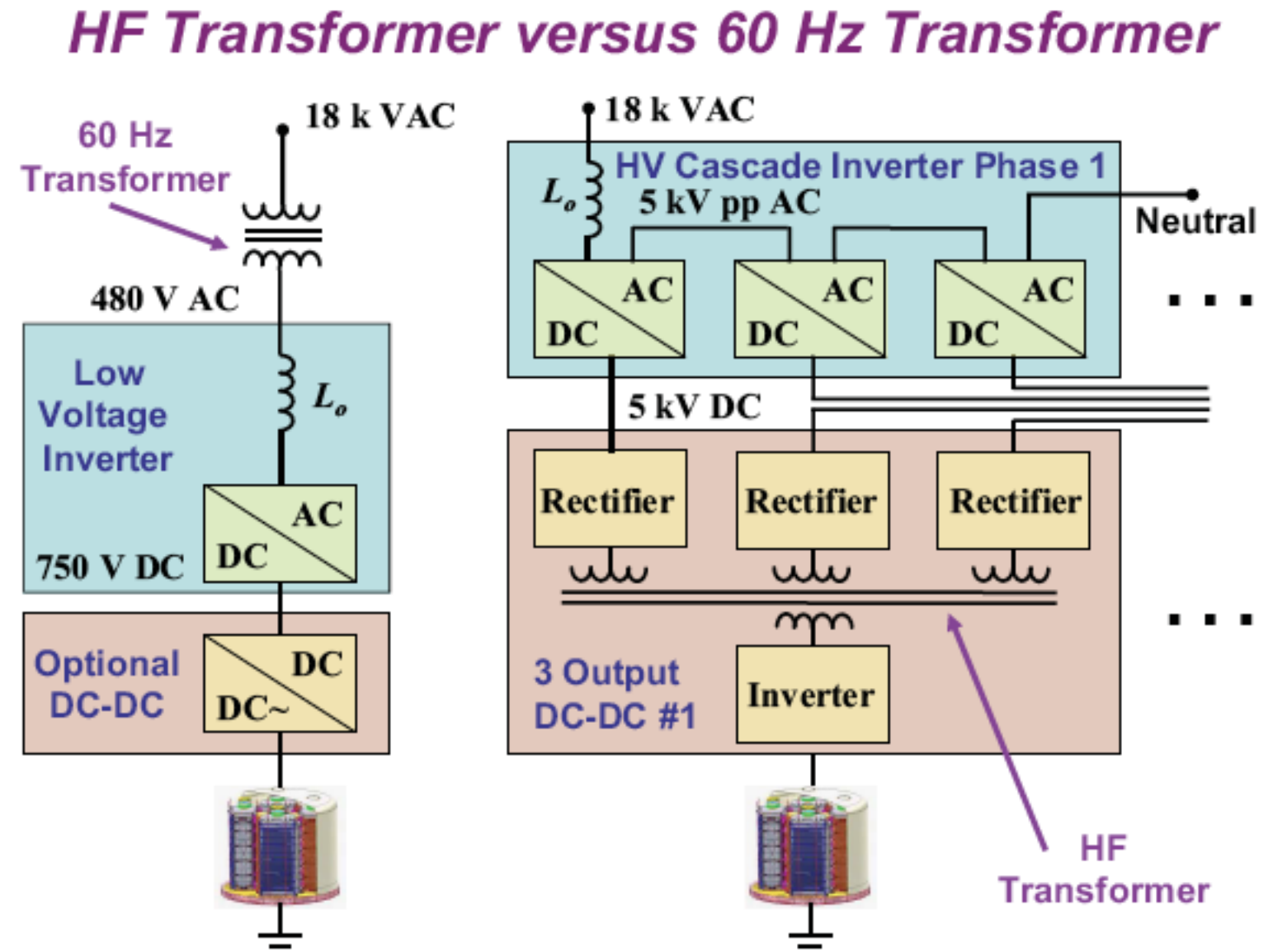
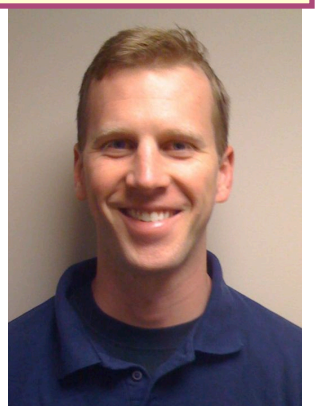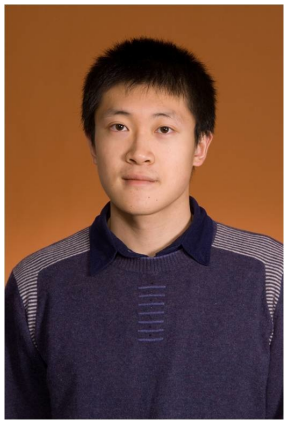
Introduction: Soft Magnetic Nanocomposites