COMPONENTS AND TECHNOLOGIES FOR HIGH FREQUENCY AND HIGH AVERAGE POWER CONVERTERS*

HIGH MEGAWATT POWER CONVERTER WORKSHOP
NIST
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Outline

- Amorphous Nanocrystalline Transformers
- High Power Capacitor Development
- High Power Resistor Development

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
- <u>450 LBS for 3</u>
- 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
- <u>35 Tons</u>
- ~30 KW Loss

Nanocrystalline Transformer Development

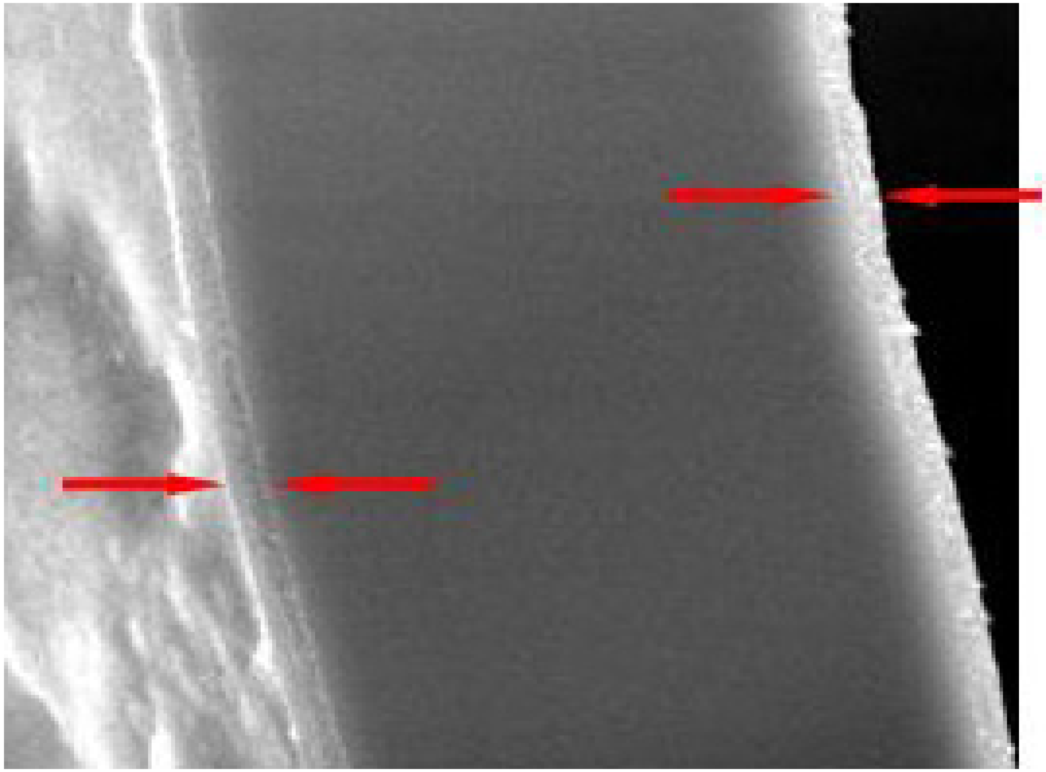
- Funding Initially Provided To Develop Process Techniques
  - Winding (Nano Shrinks ~1.5% During Processing)
    - Loose
    - Compressible Mandrel
- Processing (Exothermic Reaction)
  - Oven Temperature Control
- Stack Lamination Insulation
  - Wet Lay-Up
  - Dry
- Core Cutting
  - Water Jet, EDM, Diamond Saw
- Core Annealing
  - Dimensional Stability
- Pole Face Lapping, Etching
  - Pole Face Stack Resistance
  - Eddy Current Losses

Nanocrystalline Transformer Development

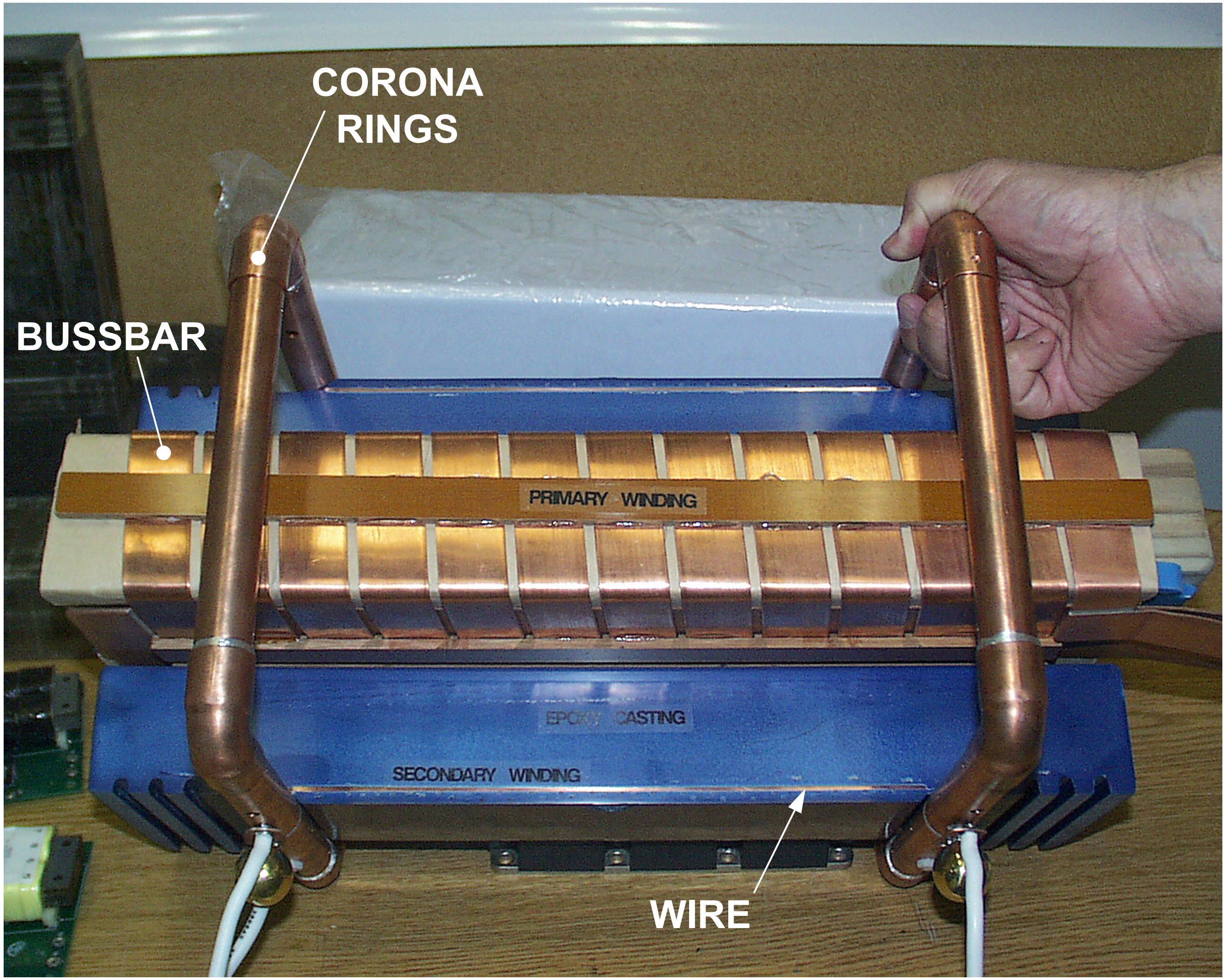
Nano Material Characteristics

Mu	100,000
Lamination Thickness	.0007"
Lamination Insulation	<1 µM
Stacking Factor	~90%
Bsat	12.3 kG
Core Loss (our use)	~300 W
Core Weight (our use)	~95 lbs
Power (each core)	330 kW

Oxide Insulating Coating



Boost Transformer Winding Design (140 kV, 20 kHz)



Recent Developments

- Wider Strip Width
  - Improved Core Geometries
- Improved Manufacturing
  - Better Experience Base
    - Better Mechanical Fabrication Techniques
    - Can Manufacture Exotic Shapes
- Improved Electrical Performance
- More Vendors
  - Japan (Hitachi)
  - Russia
  - Germany (VacuumSchmelze)
  - China

Advanced Transformer Geometry

- Polyphase Y
- Ring And Bar
- Triangle And Bar

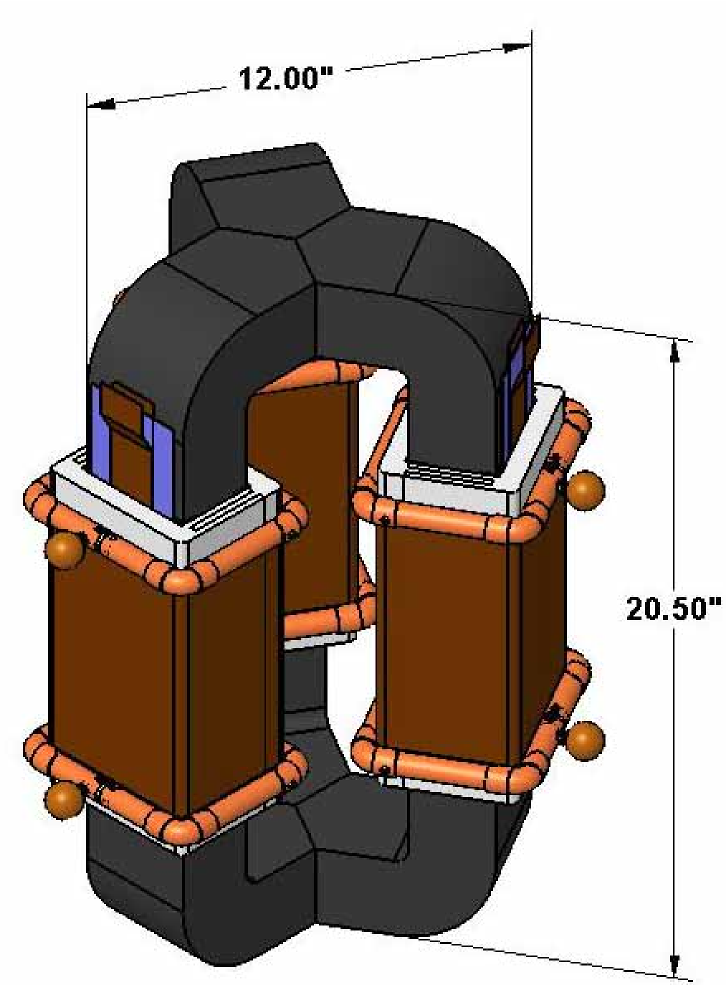
Polyphase Y

ADVANTAGES

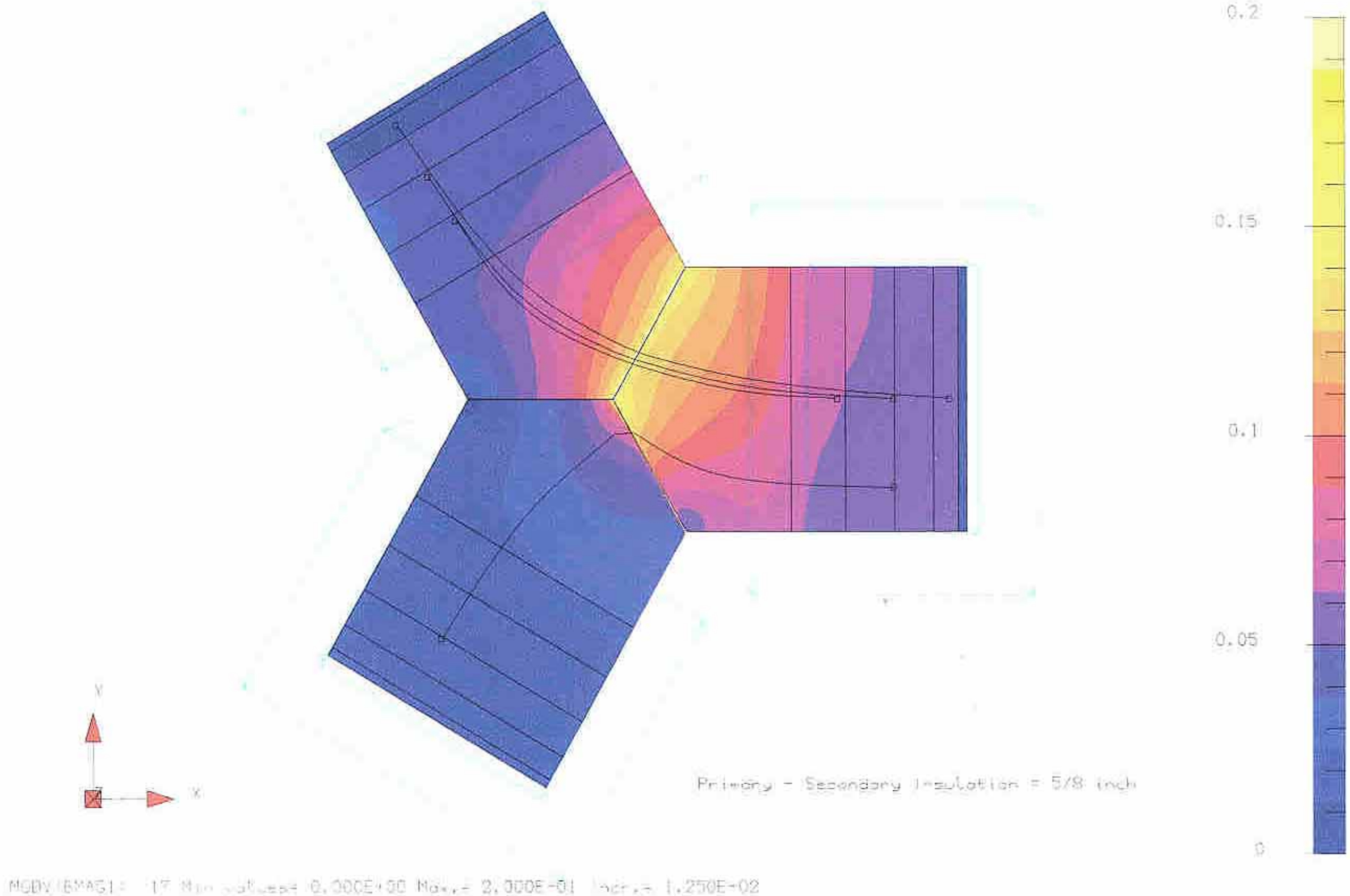
- Good Flux Balance
- Highest Performance
- 2 Gaps Per Winding Pair

DISADVANTAGES

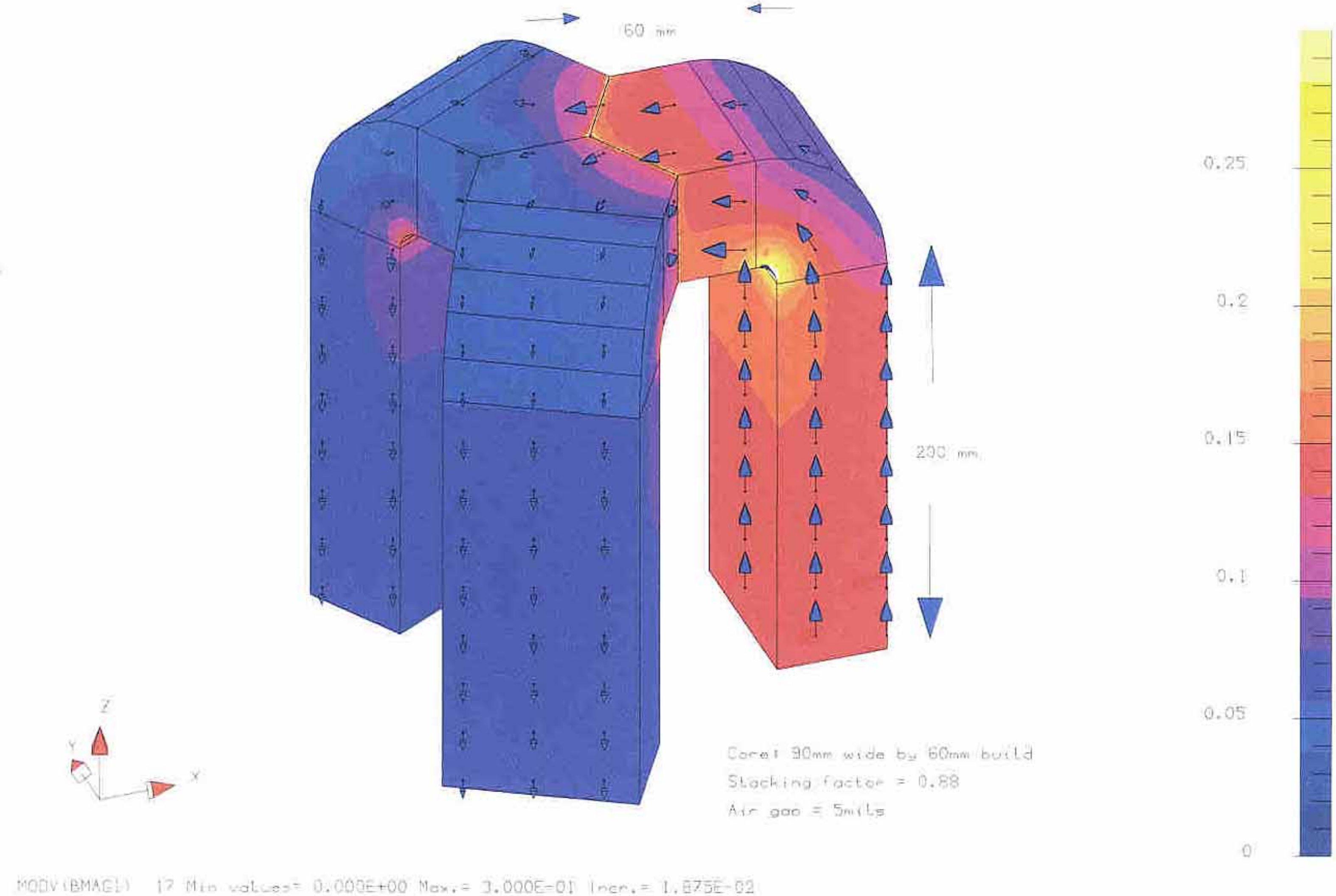
- Windings On Core
- Hard To Manufacture
- Sensitive To Tolerances
- Could Not Manufacture Previously



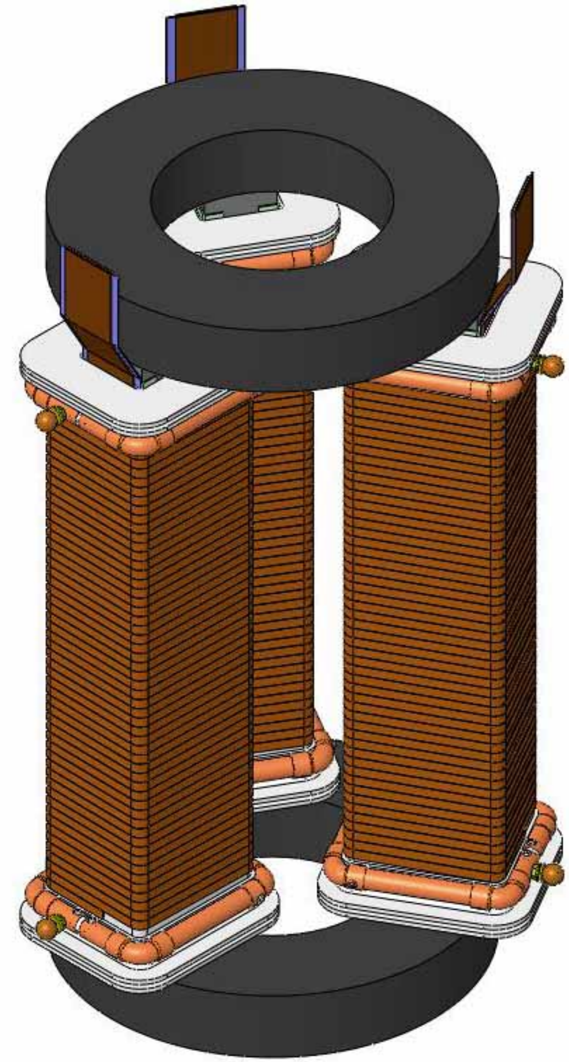
Flux Asymmetry Caused By Chamfer



Flux Concentration On Inner ID



Ring Bar Transformer



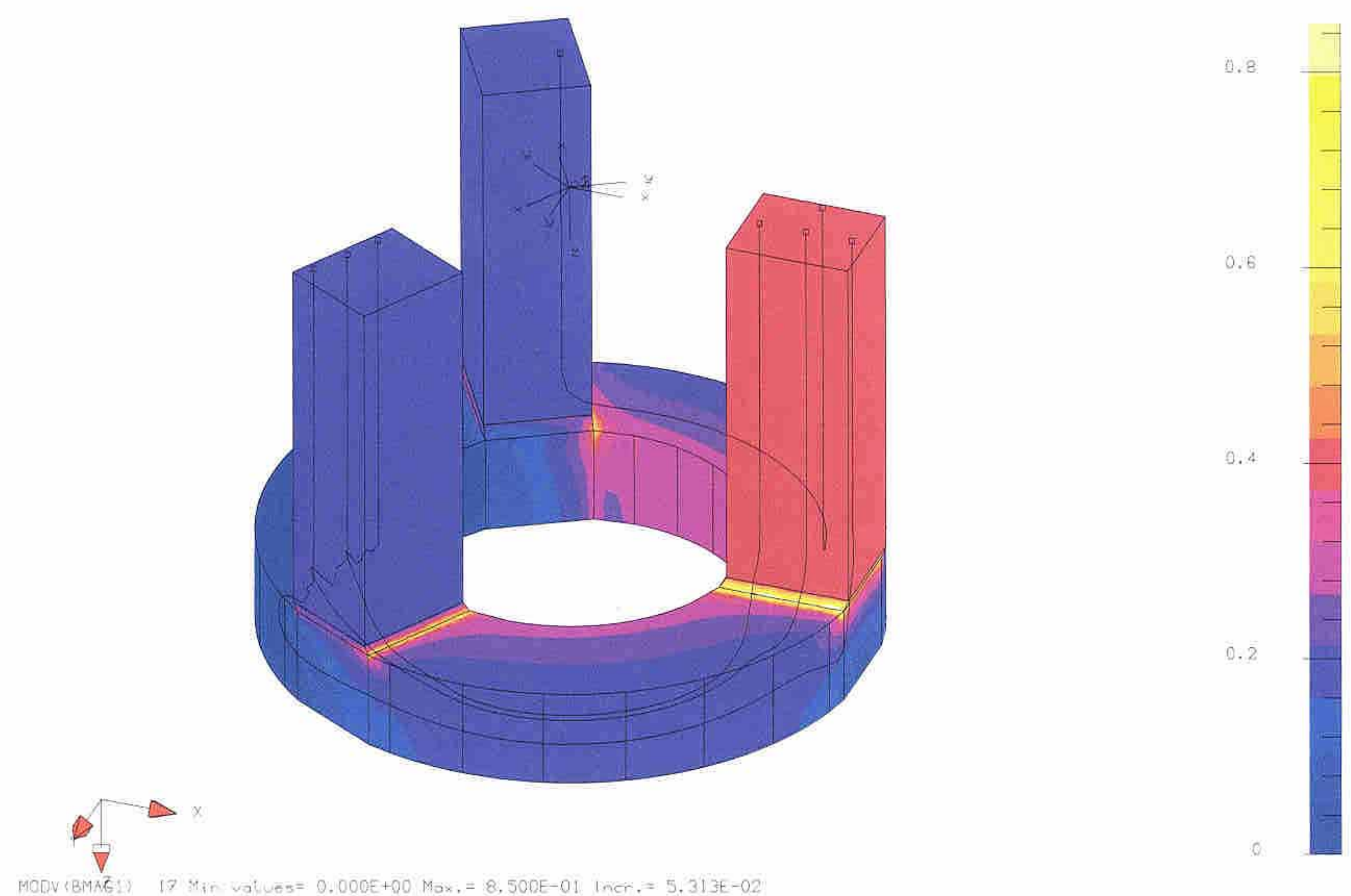
ADVANTAGES

- Simple Topology
- Can Use Winding Bobbins

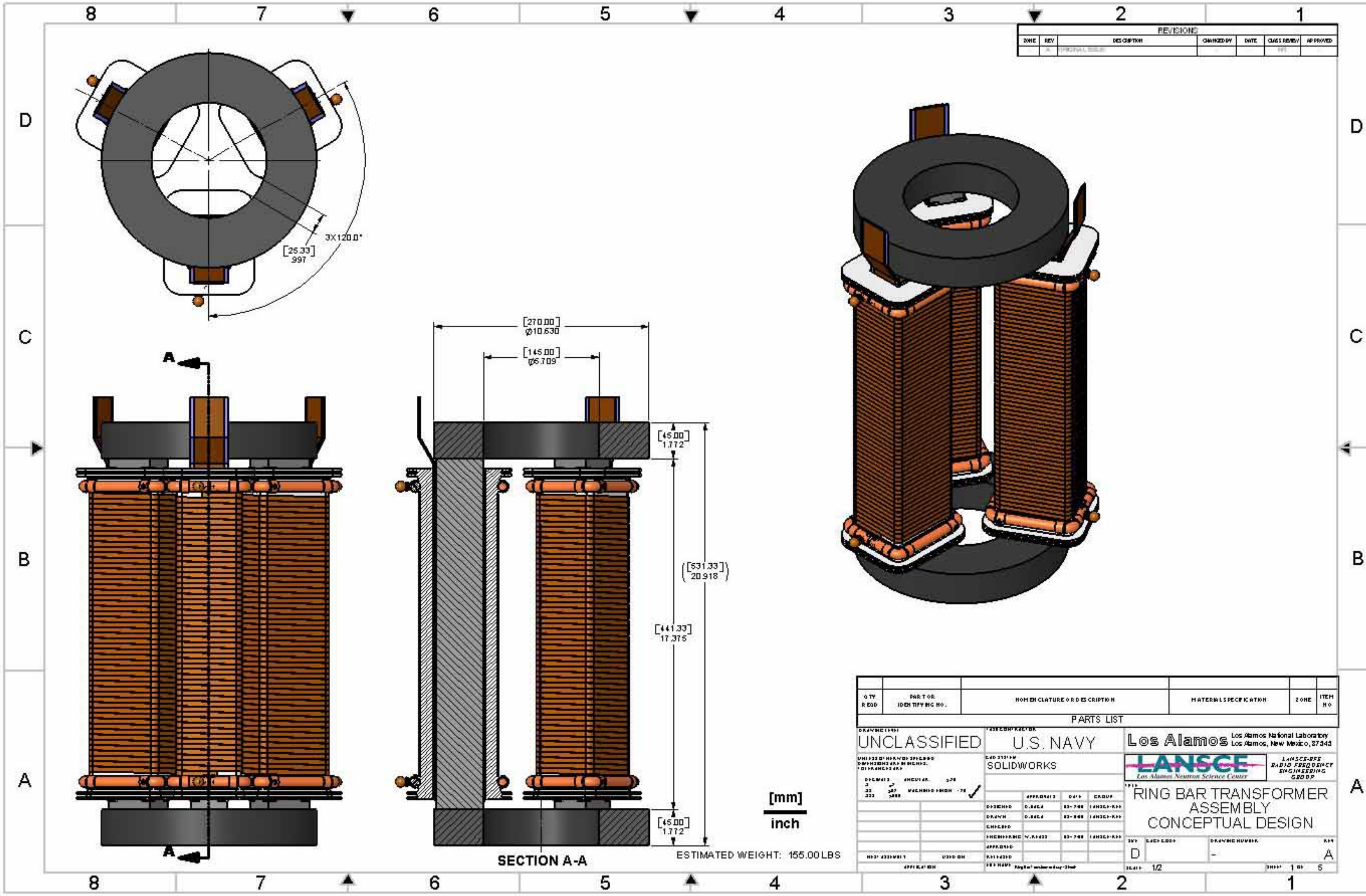
DISADVANTAGES

- Higher Reluctance Path
- 2X Core Gaps
- Mechanical Robustness (?)
- Secondary Tabs On Narrow Dimension

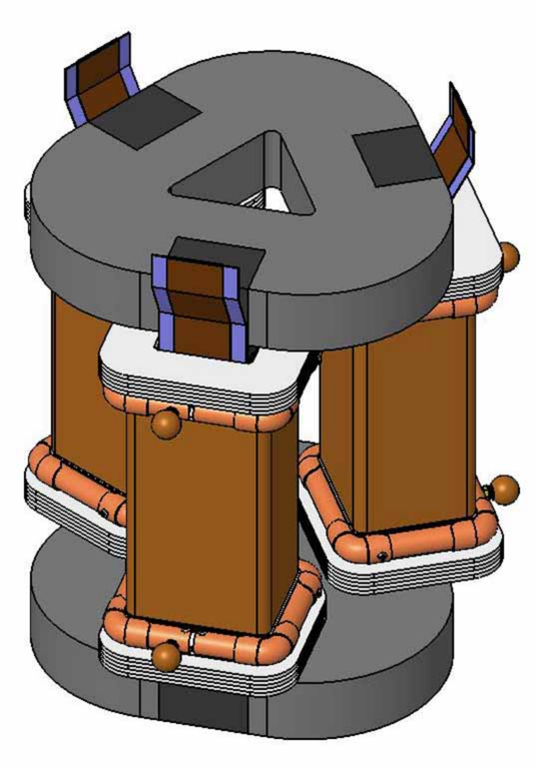
High Flux Concentration At Interface



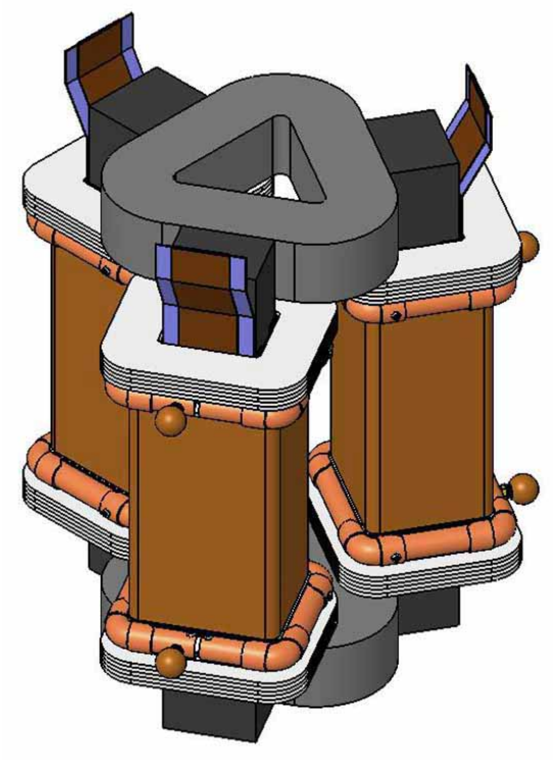
Ring Bar Transformer–Conceptual Design Drawing 1



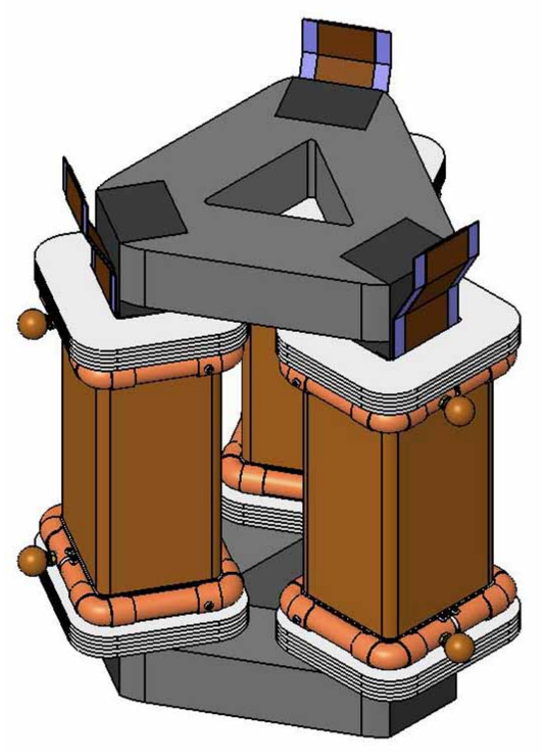
Triangular Bar Transformer Design Possibilities



OPTION 1



OPTION 2



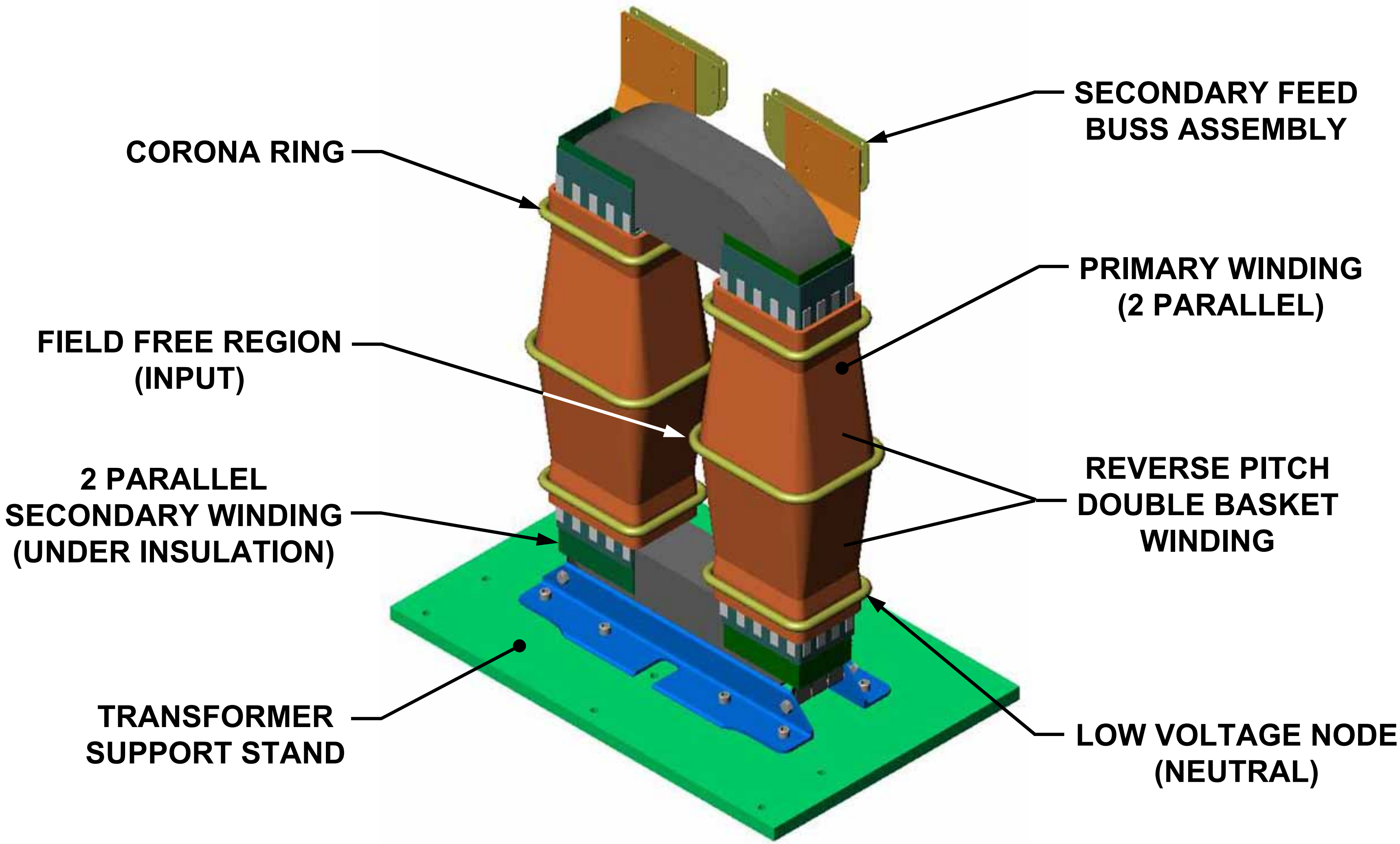
OPTION 3

Flux Concentration At Corner And Interface

Design Example of a 13.8 kV “Y” Input, 460 V “Δ” Output with a 2.7 MVA Overall Electrical Rating (Advanced Core Design)

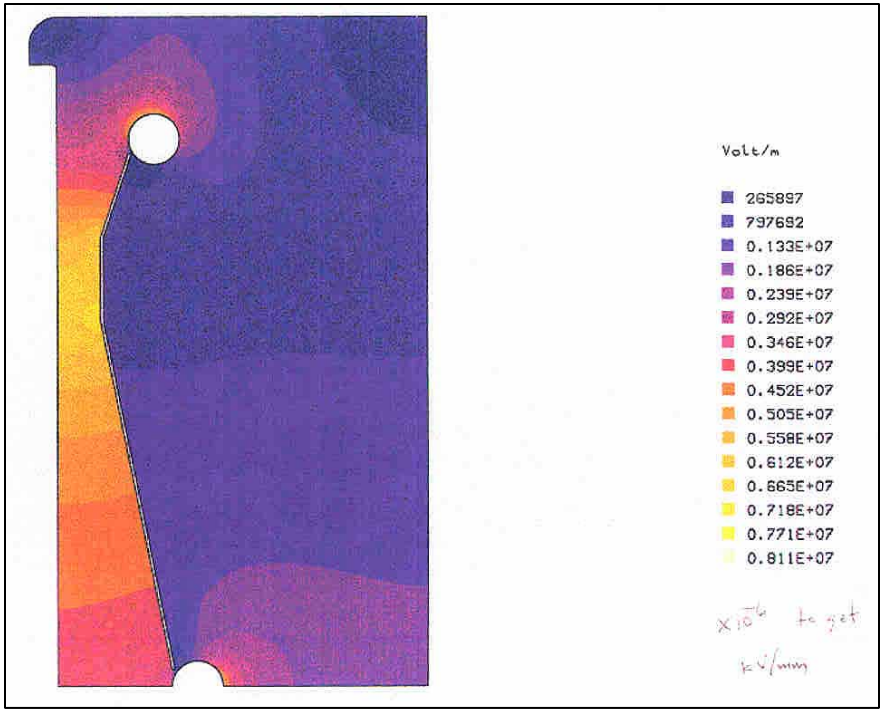
- Core Loss
  - 20 KHz And ~7 KG
  - 30 W / lb (125 lb)
  - ~4 KW
- Primary Loss
  - 2 KW
- Secondary Loss
  - 4 KW
- Overall Efficiency
  - ~99.6%

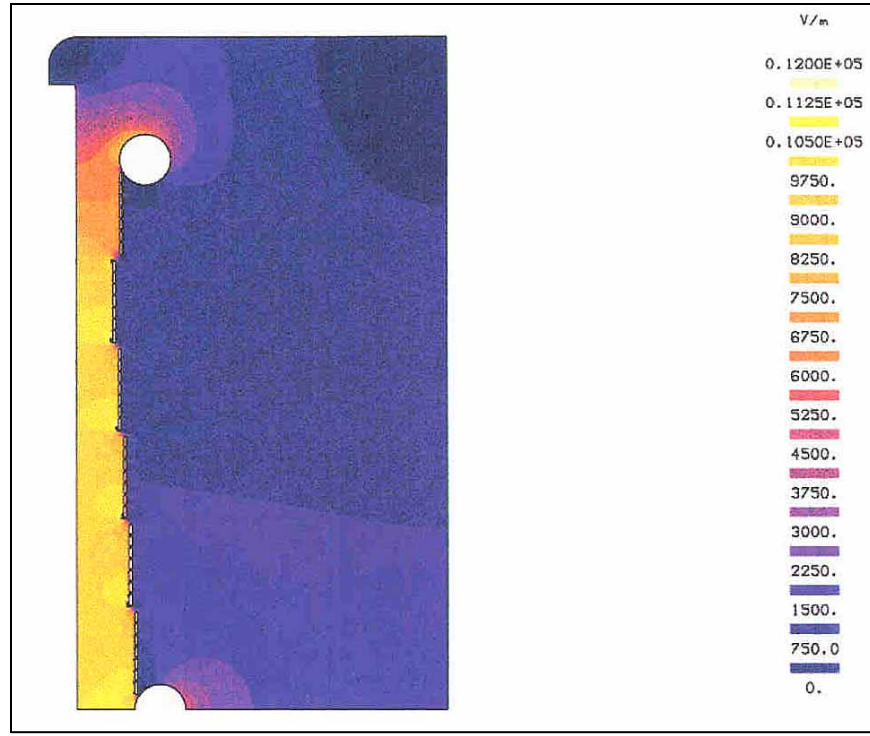
C-Core Designs Offer Higher Efficiency



Advanced Winding Topology Minimizes Field Stresses And Leakage Inductance

Winding Taper Improves Performance



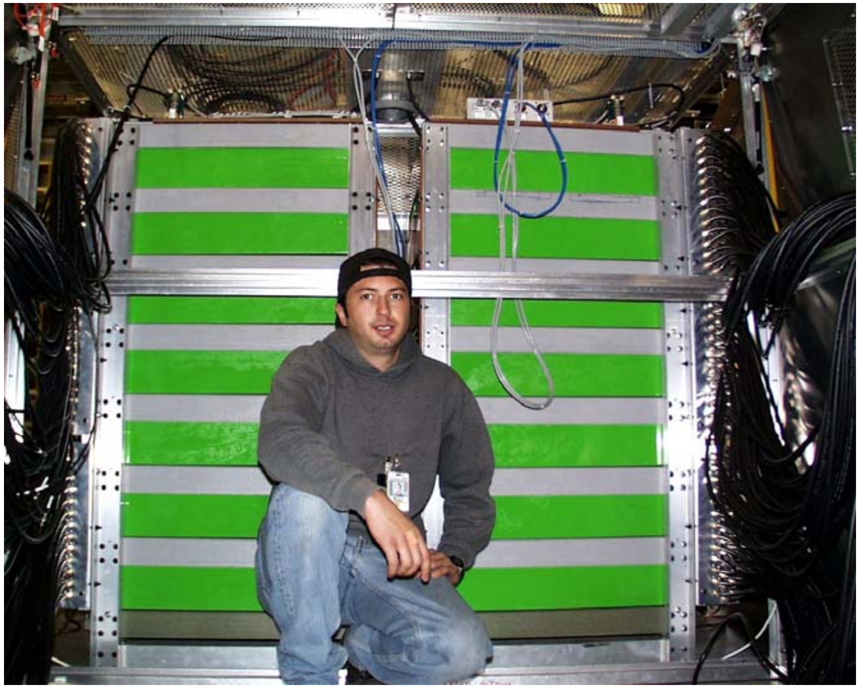


- Lower Field Stress
- Lower Leakage Inductance
- Minimized End Effects

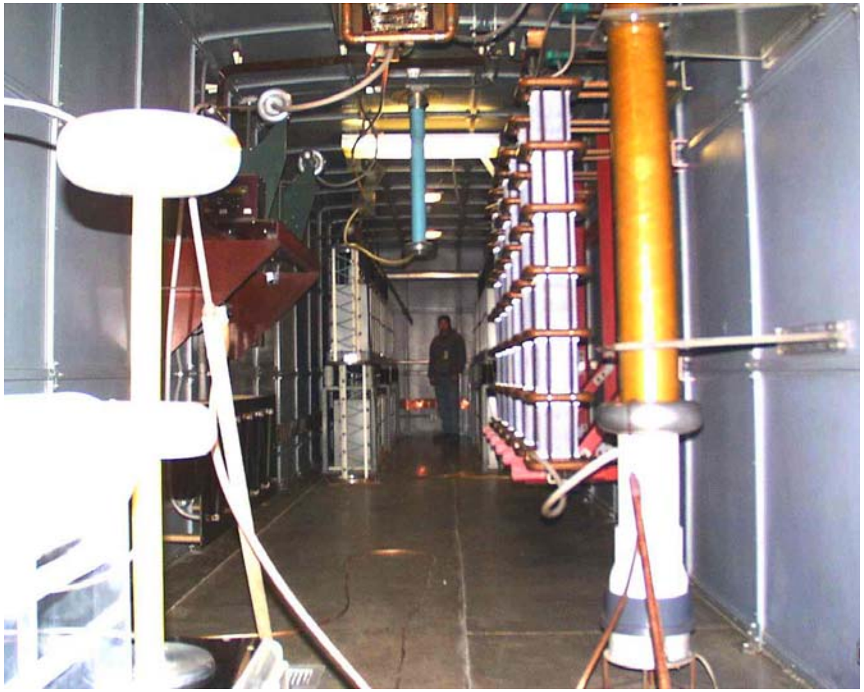
What We Need to Also Consider

- Examine Start-up Sequence To Prevent Core Saturation
  - Prevent Excessive Fault Currents
- Examine Neutral Node Commutation Transients
- Examine Core Pole Piece Interface Design To Minimize Flux Concentration And Losses
- Optimize Design to Application For Increased Efficiency
- Optimize Winding Design For Minimized Field Stress And Leakage Inductance

Self-Healing Metallized Hazy Polypropylene Energy Storage Compared To Conventional High Voltage Method (Paper and Foil) Is Very Compact And Reliable

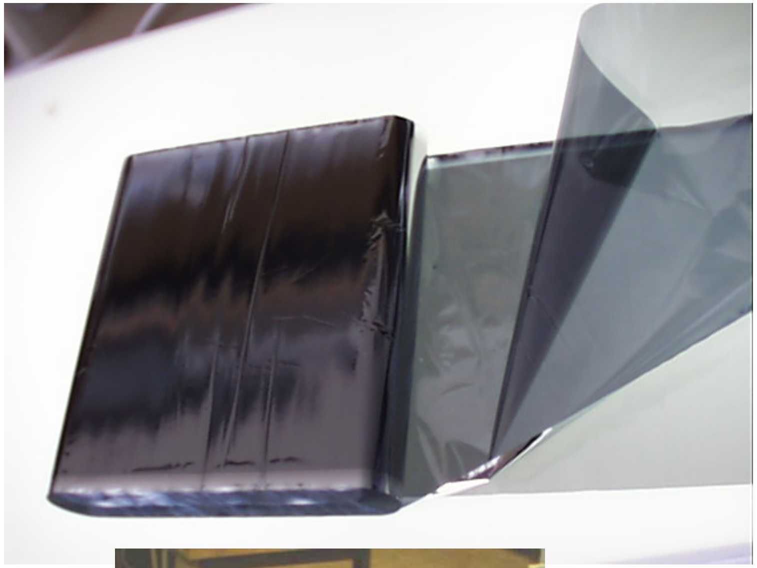


- 300,000 hour lifetime
- Graceful degradation
- High frequency design
- High volumetric efficiency
- High safety factor



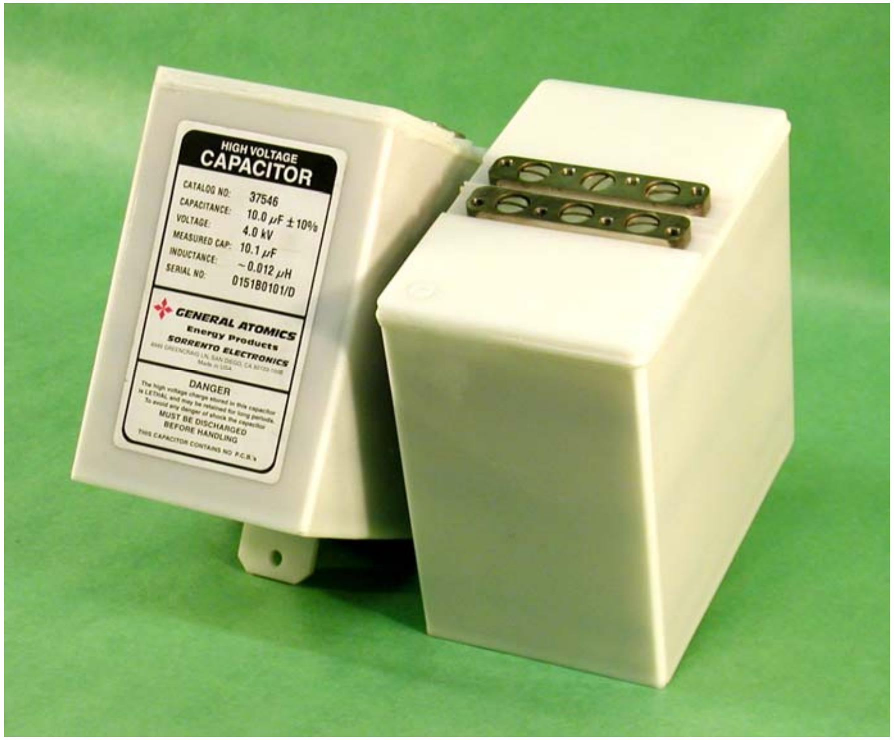
- Limited lifetime
- Explosive failure modes
- Highly frequency dependant and lossy
- Large footprint
- Poor safety factors and dangerous

Ultra-Low Inductance (L~ 15 nH) 20 kHz High Current DC Buss Link Self-Healing Capacitor Construction



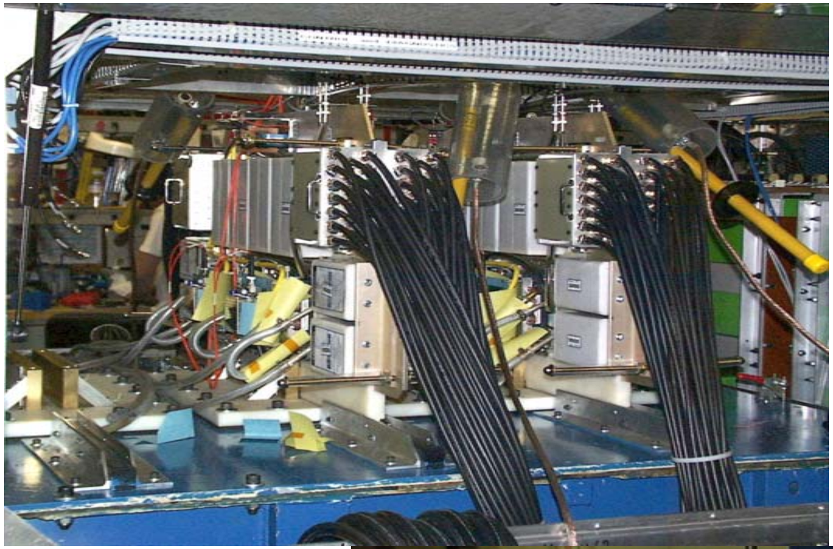
General Atomics High Power Foil Capacitors

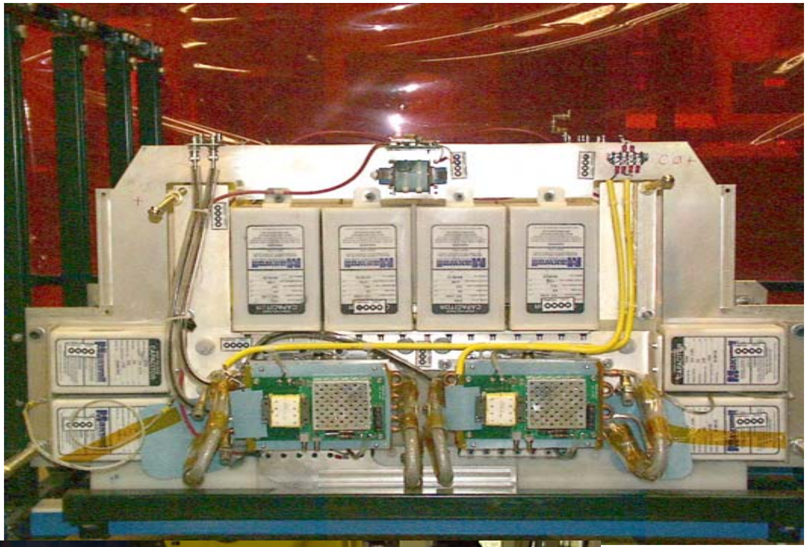
<u>Transformer Resonating Capacitor</u>
3100pF, 120kVDC, 85kVAC,
3.5 MVAR
(Composite Dielectric)

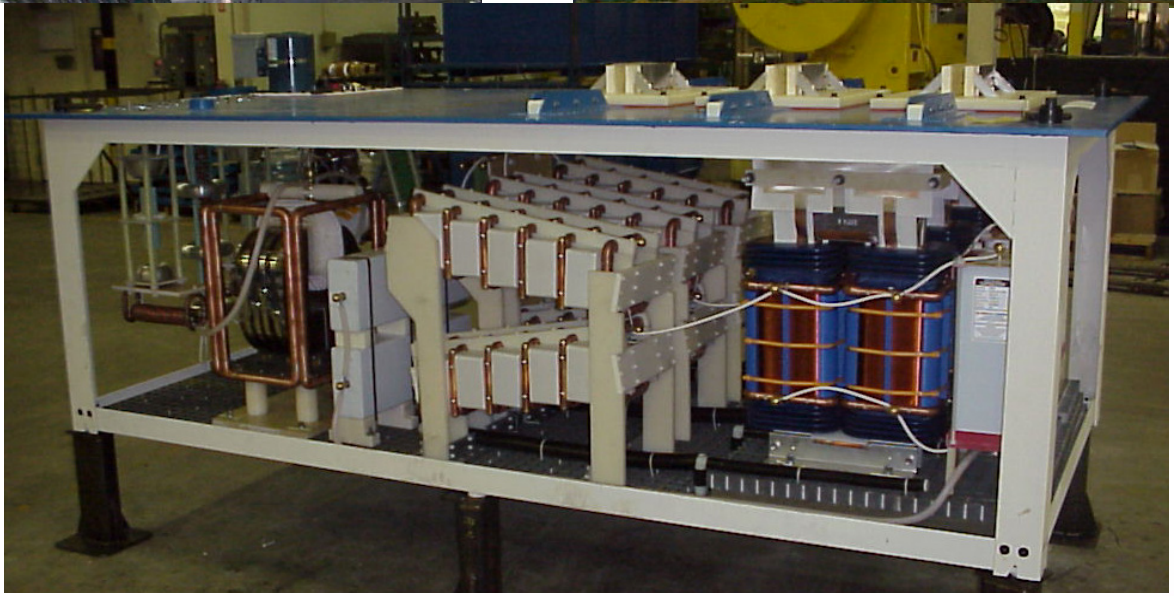


<u>IGBT Bypass Capacitor</u>
10μF, 4kV
250 ARMS @ 20KHz
(Plastic Dielectric)

Example of High Power Capacitor Use (10 MW Long Pulse Polyphase 20 kHz Resonant Converter)







Recent Capacitor Improvements

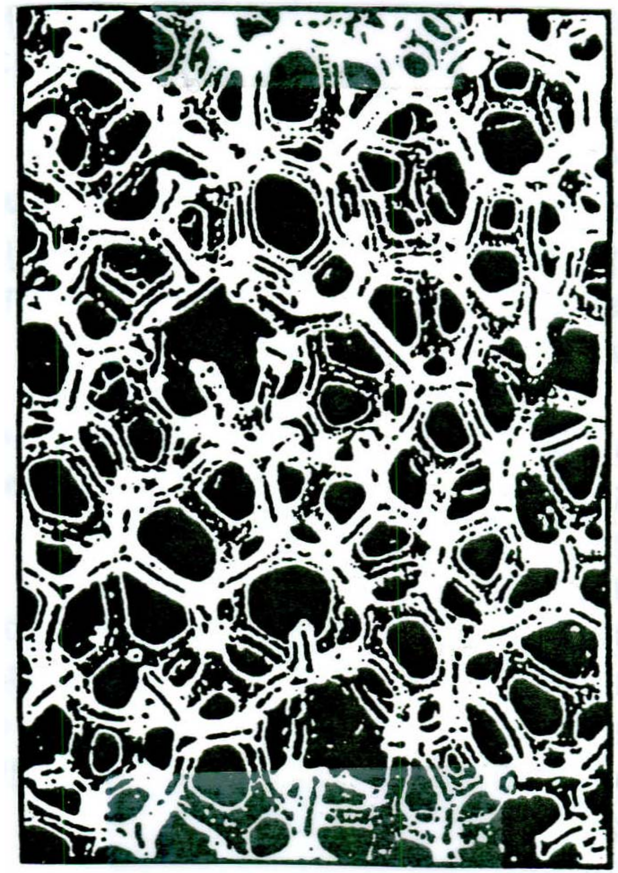
- Improved Winding Techniques
  - Smaller
- Improved Dielectric Oil
  - Lower Loss
- Better Understanding of System Requirements
- Thinner Dielectrics
- Recent “Record” Energy Densities in Polypropylene Pulse Power Capacitors
- Other Programmatic Pushes
- Many Players

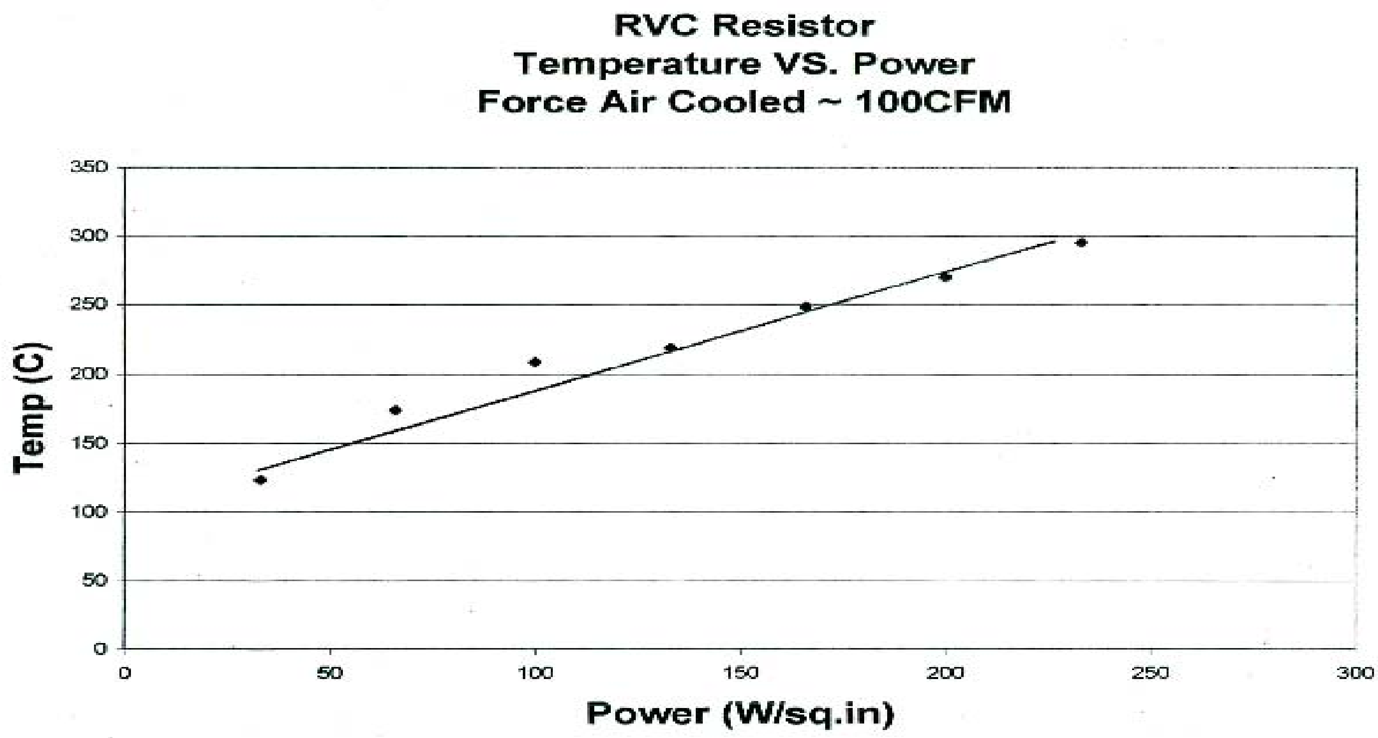
High Power Resistor Development

- Many Types of Resistors
  - Film
  - Wire Wound
  - Ribbon Wound
  - Carbon Composition
    - Organic
    - Ceramic
- All Suffer From Problems
  - Inductance
    - Wound varieties
  - Voltage Gradient or Current Density
    - Composition (grain boundary issues)
  - Film
    - Energy (Fault) Capability
- Power Resistors Are Not Desired
  - May be useful in (high power) snubber circuits

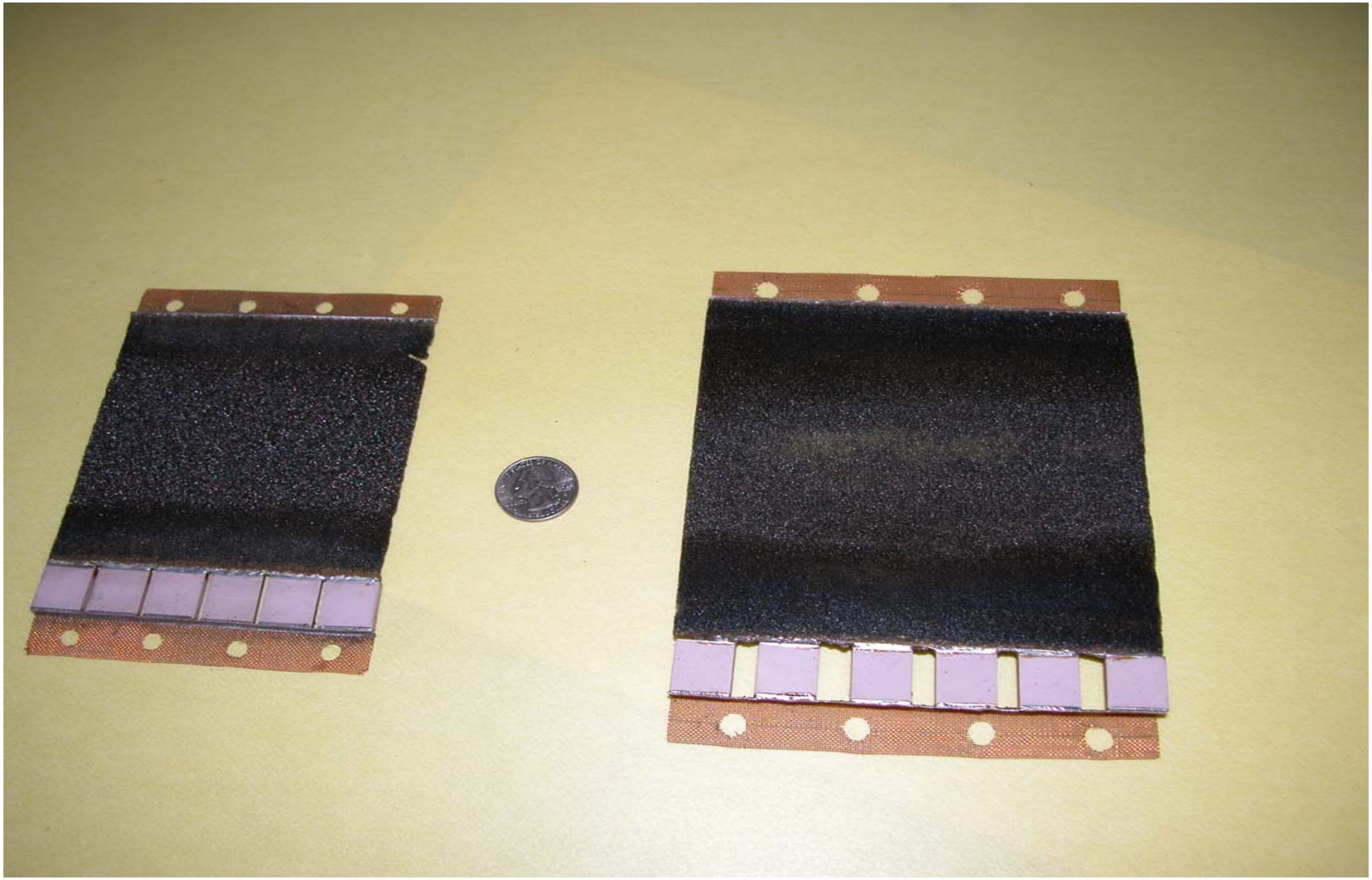
Reticulated Vitreous Carbon (RVC) Foam High Power Resistors Developed at LANL

- A Glassy Carbon Available with Various Ligament Diameters, Porosities, and Densities.
  - Can engineer low inductance, high power resistors
- LANL Has Tested To:
  - >15 kA / cm2
  - Pulsed Currents to 850 kA
  - Circuits to 120 kV
  - 130 J / cc in air
  - 25 J / cc in oil
  - 250 W / sq in (air)
- "Δ" R = 0, Does Not Absorb Oil or Water
- Has "Infinite" Surface Area, Should Be Capable of "Infinite" Power




RVC Resistor
Temperature VS. Power
Force Air Cooled ~ 100CFM
Temp (C)
0
50
100
150
200
250
300
350
Power (W/sq.in)

EXAMPLE OF "RVC" LOW INDUCTANCE HIGH POWER SNUBBERS



CONCLUSION

- MANY TECHNOLOGIES DEVELOPED FROM EUROPEAN TRACTION MOTOR INDUSTRY
  - WE CAN LEVERAGE THOSE COMPONENTS TO OUR DESIGNS

- MANY CONVERTER TOPOLOGIES AND TECHNIQUES DEVELOPED BY U.S. INDUSTRY

- COMPLEMENTARY TECHNOLOGIES ALSO DEVELOPED AT THE NATIONAL LABORATORIES
  - High Average Power Systems
  - Pulsed Power Systems

- NATIONAL LABORATORIES ARE AVAILABLE TO HELP
  - Teaming is part of our charter.