



Transformers | Motors | Generators

| 19-21 May 2026

● A Hyve Event



University of
BRISTOL



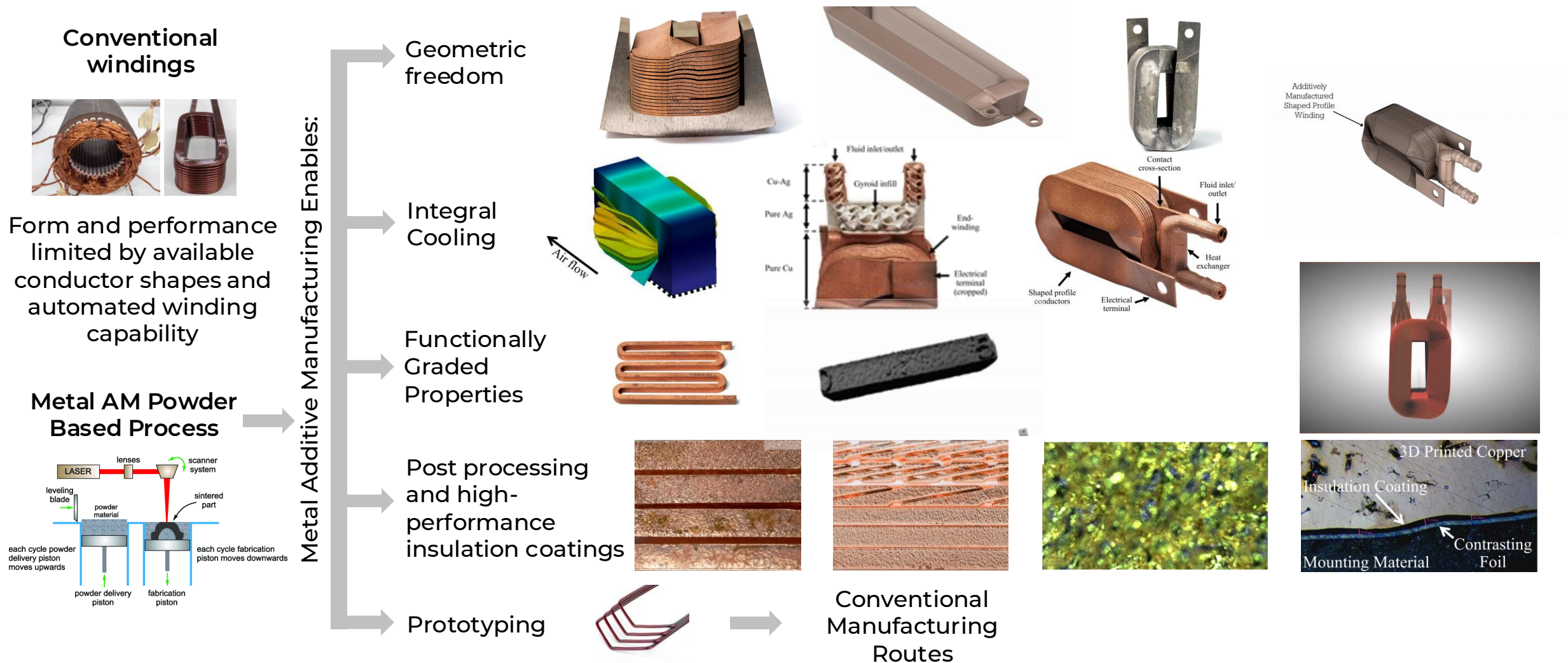
THE ELECTRICAL
MACHINE WORKS

High-Performance Electrical Machine Windings Enabled by Metal Additive Manufacturing

Dr Anna Ermakova – University of Bristol, 32B14 (Hall 3.2)



The Electrical Machine Works (TEMW)



Power-to-weight, efficiency and integrity targets unlikely to be achieved through incremental development.



Additive Manufacturing of Electrical Machines

WP1: Flexible Design Tools for Additive Manufacturing of Coils

WP2: Measurement Protocol for Electrical Properties of Additively Manufactured Materials

WP3: Demonstration of Robust Electrical Insulation under Representative Operating Conditions

WP1: AM Design Tools

The Problem:



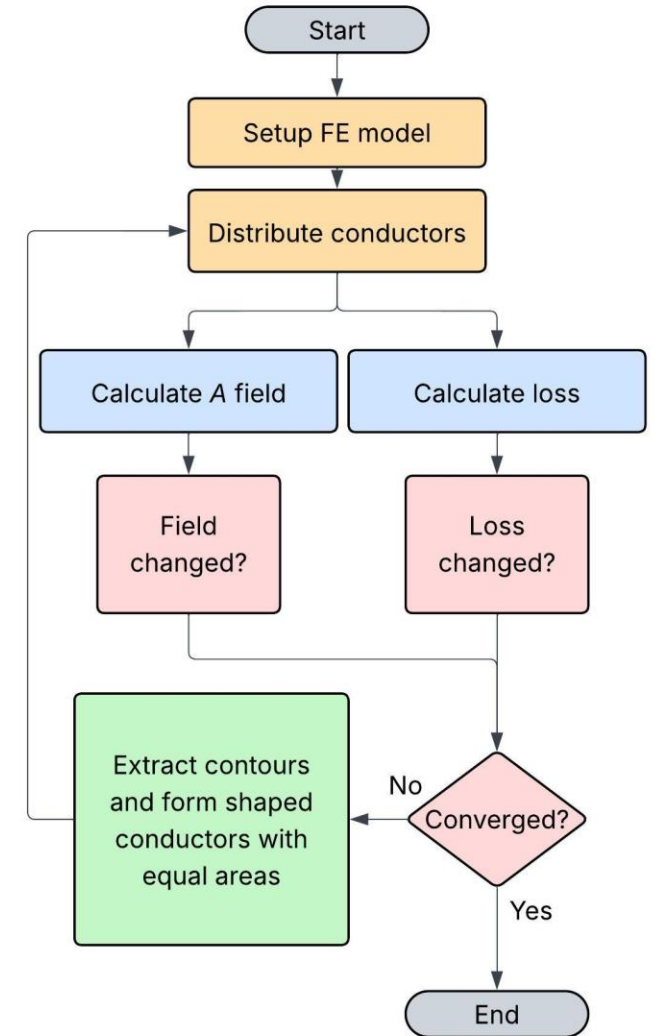
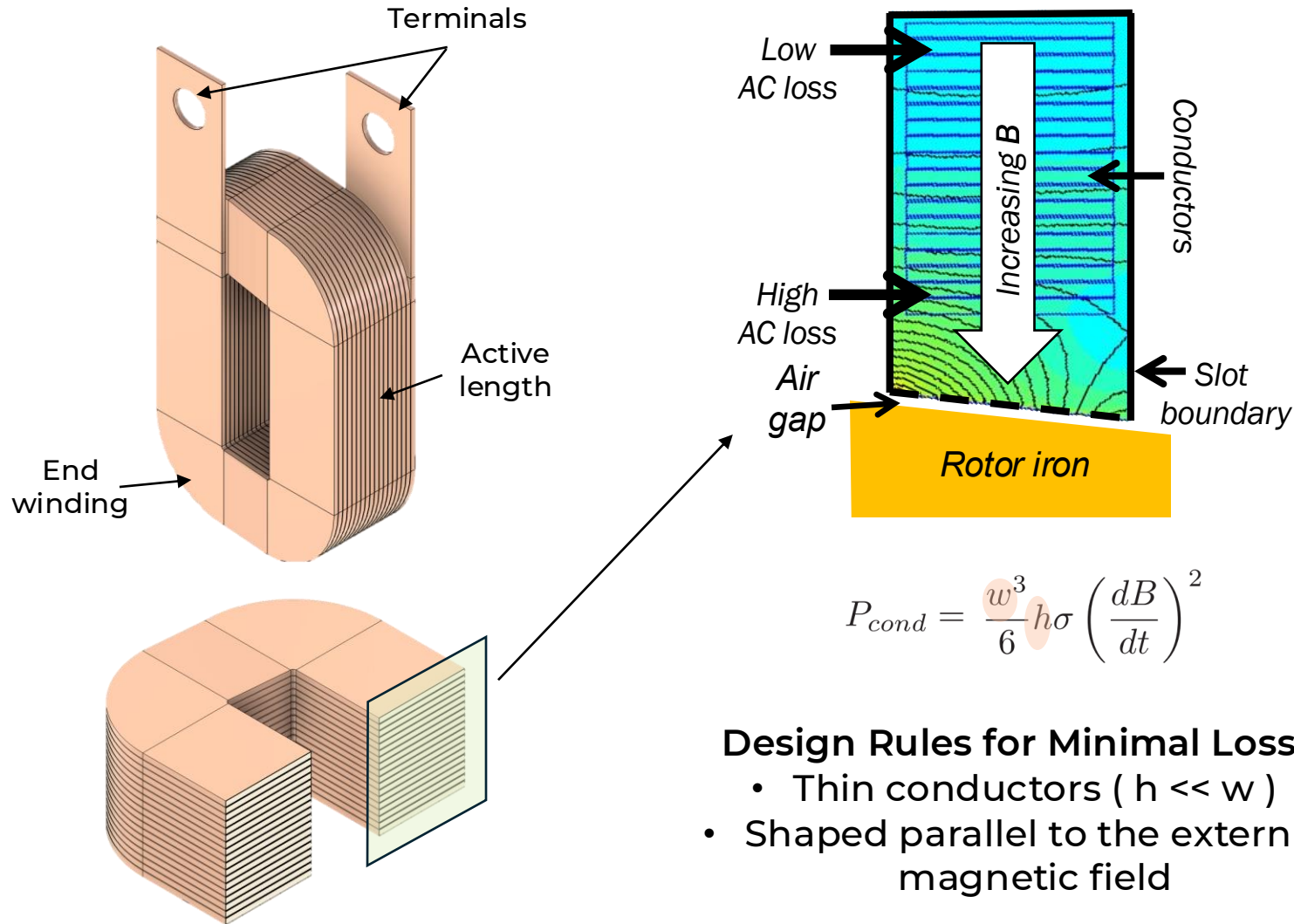
Additive Manufacturing offers unparalleled design freedom.

Which coil geometries to manufacture with AM?

How can we predict and improve efficiency of AM coils?

WPI: AM Design Tools

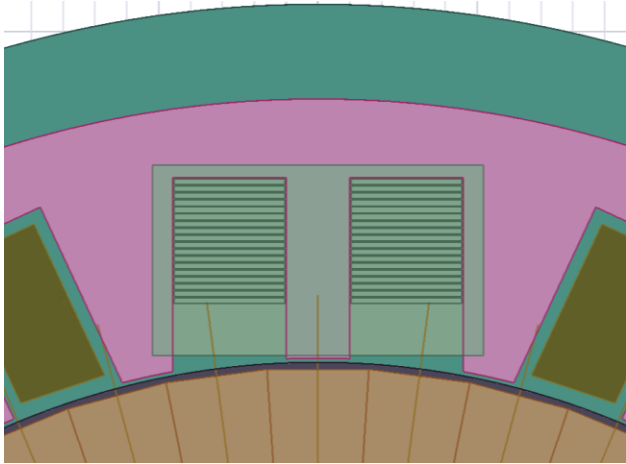
A Solution:



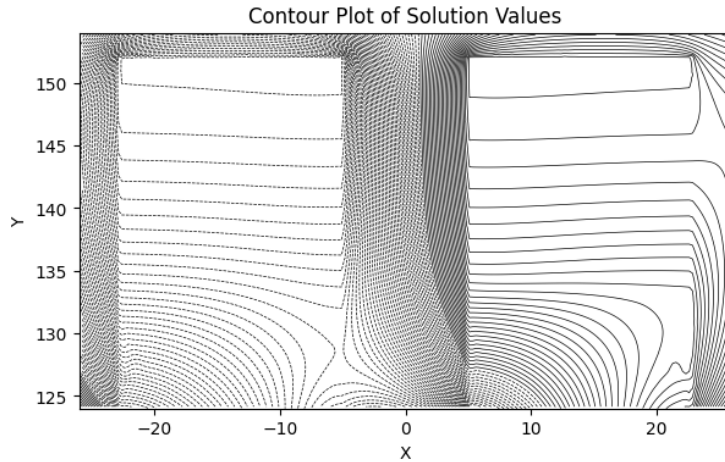
Conductor shaping algorithm

WP1: AM Design Tools

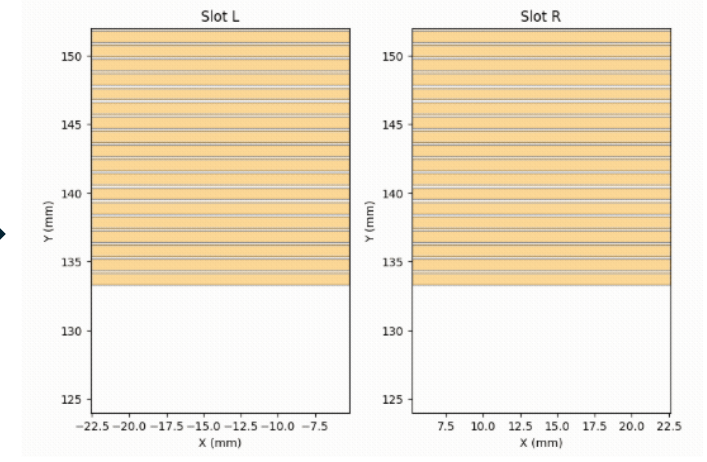
Conductor shaping algorithm:



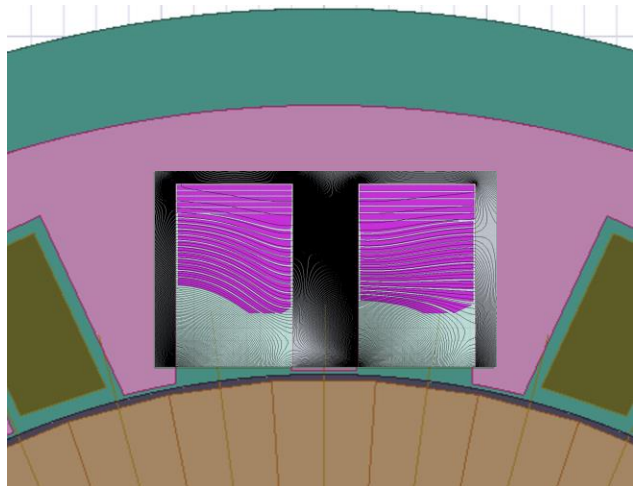
FE Model with original conductors



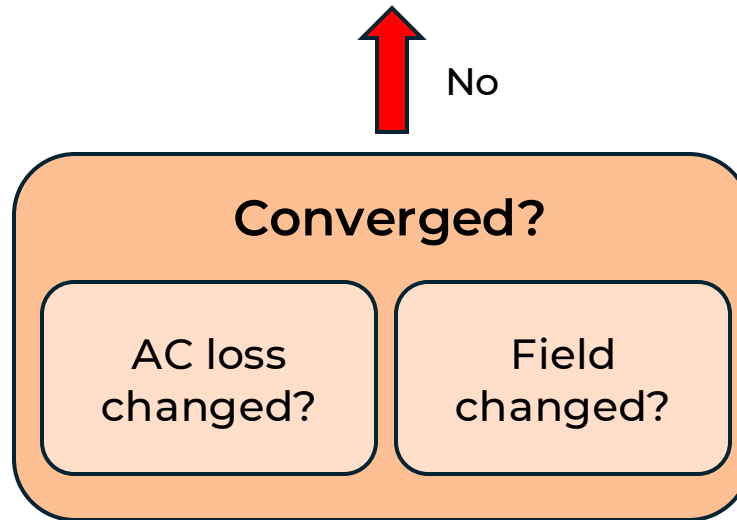
Extract magnetic field contour lines



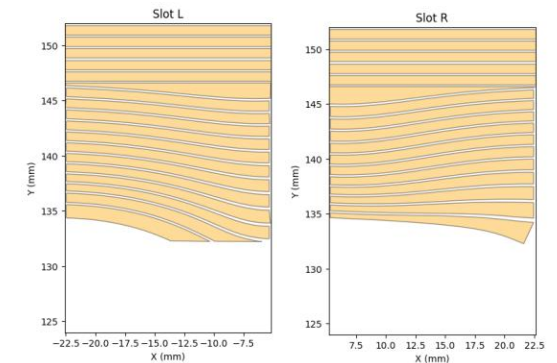
Shape conductors to match flux lines



FE Model with shaped conductors



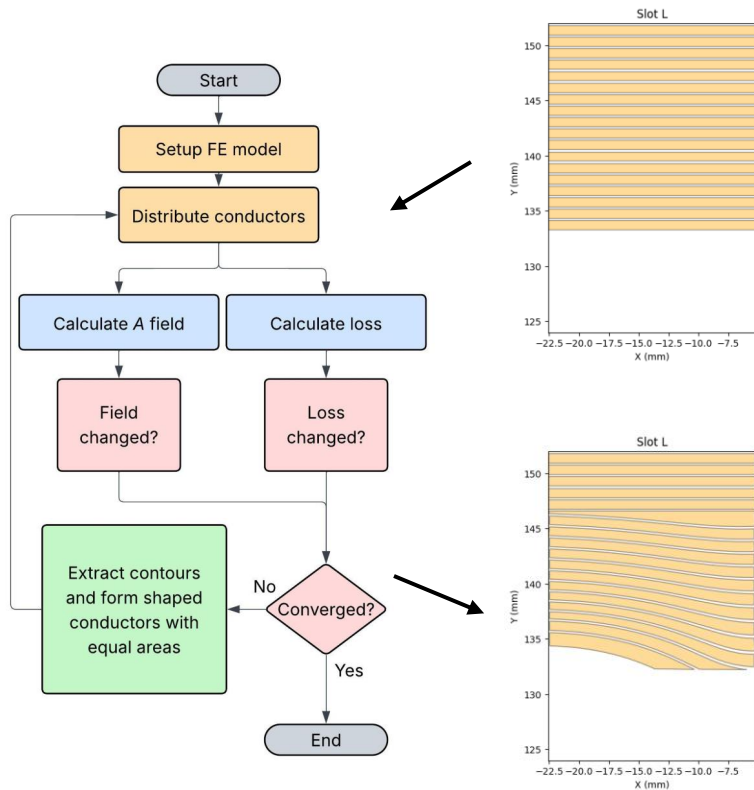
Optimisation complete:



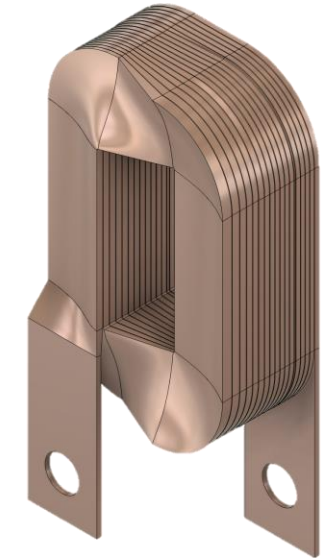
Optimised conductors

WP1: AM Design Tools

Step 1



Step 2

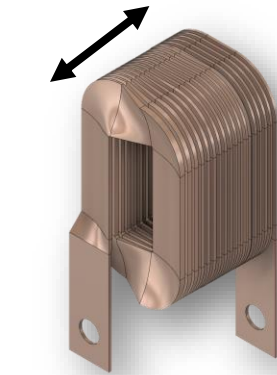
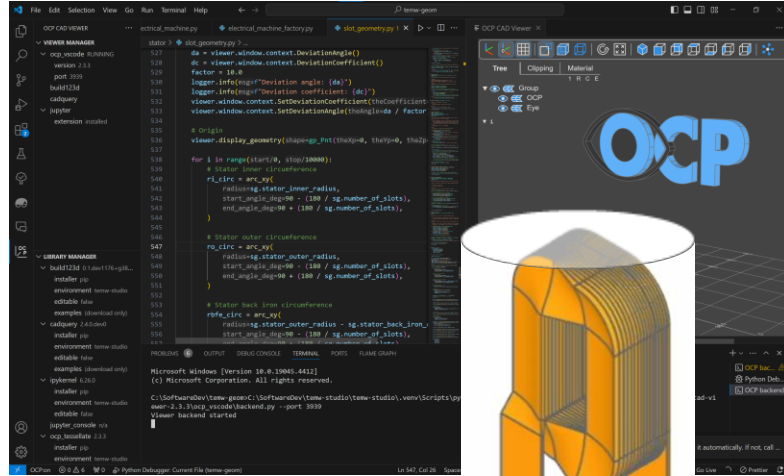


Step 1: Conductor shape optimisation tool

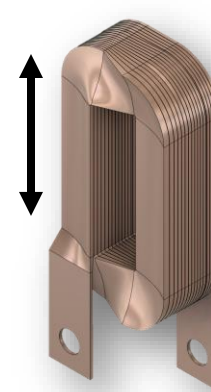
Step 2: Automated geometry generation tool

WPI: AM Design Tools

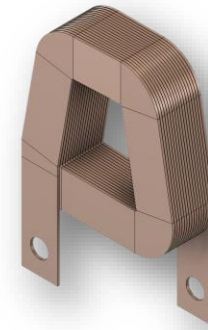
Geometry generation tool



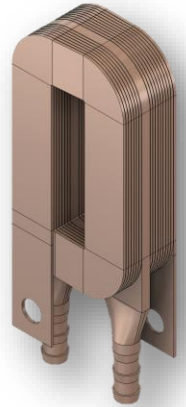
Splayed for manufacturing



Active length

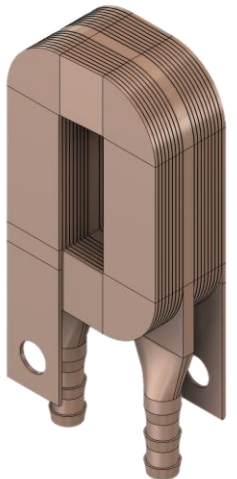
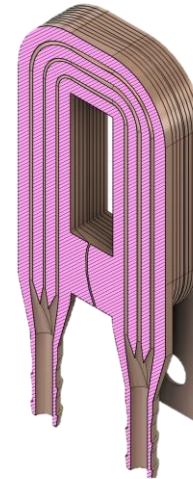
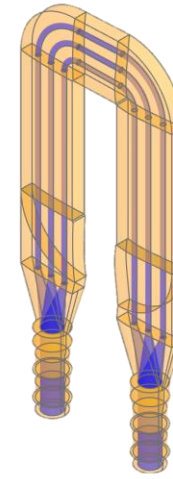
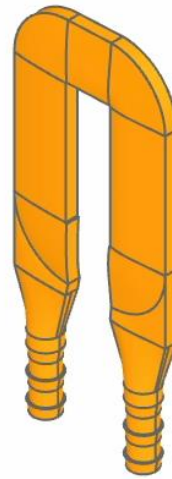
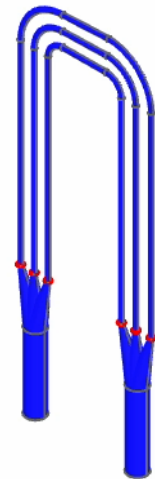


Axial angle



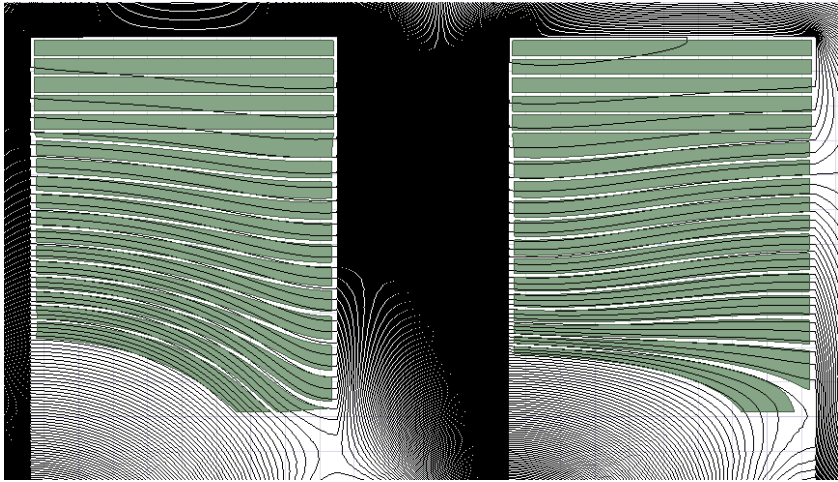
Cooling channels

Integrated cooling channels for thermal management

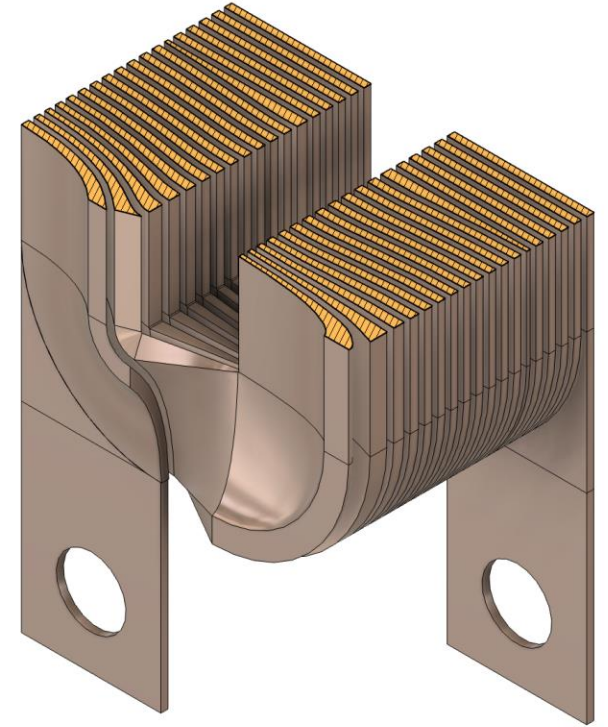
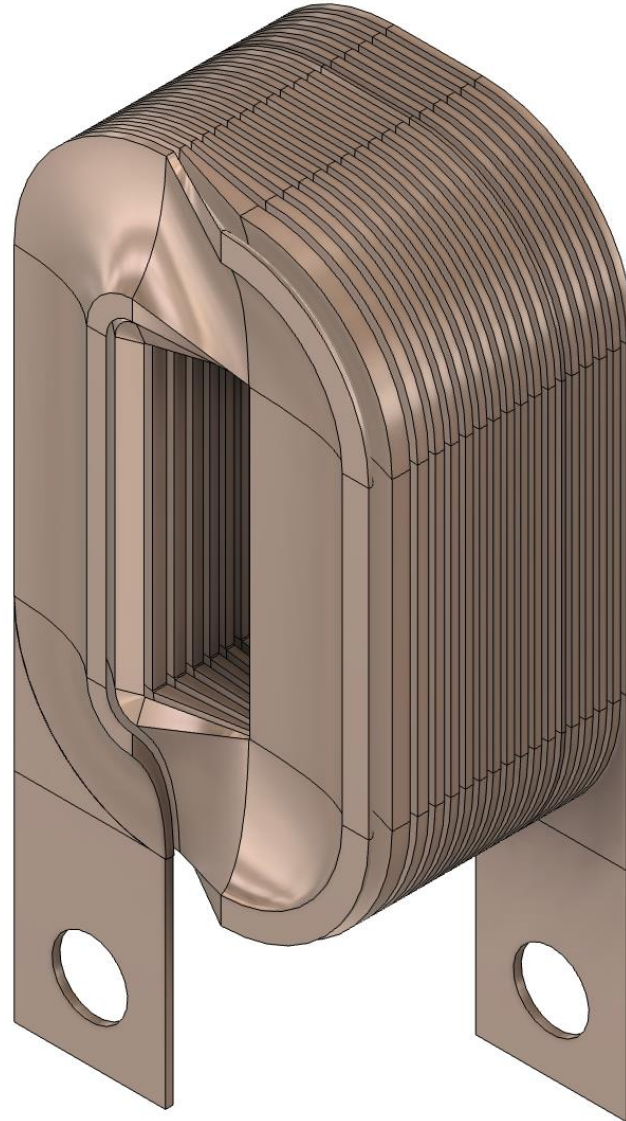


WP1: AM Design Tools

Case Study: Field-aligned AM coil geometry for lower AC loss



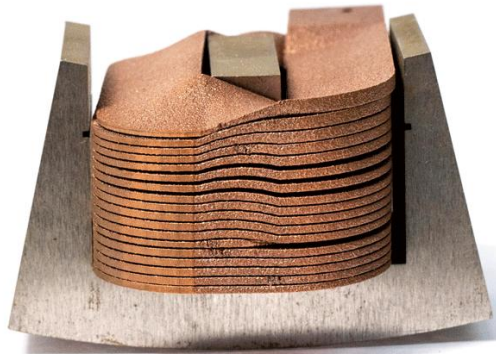
Optimised conductors
(**42% AC loss reduction**)





WP2: Measurement Protocol for Electrical Properties

The Problem:



AM Winding

What conductivity does it have?
What is its temperature coefficient
of resistance?
How do we measure it?



Cannot predict efficiency
and power density of the
machine



WP2: Measurement Protocol for Electrical Properties

Conductivity measurements:

Eddy Current Method



- ✗ Highly sensitive to surface roughness, lift-off effect, probe calibration
- ✗ Accuracy does not comply with ASTM B193
- ✗ Useful for sorting of nonmagnetic material, not for establishing conductivity values of new materials (ASTM E1004-17)

4-Wire Resistance Method



- ✓ Aligned with ASTM B193 standard
- ✓ Determines bulk conductivity of a defined sample geometry
- ✓ Easy to operate

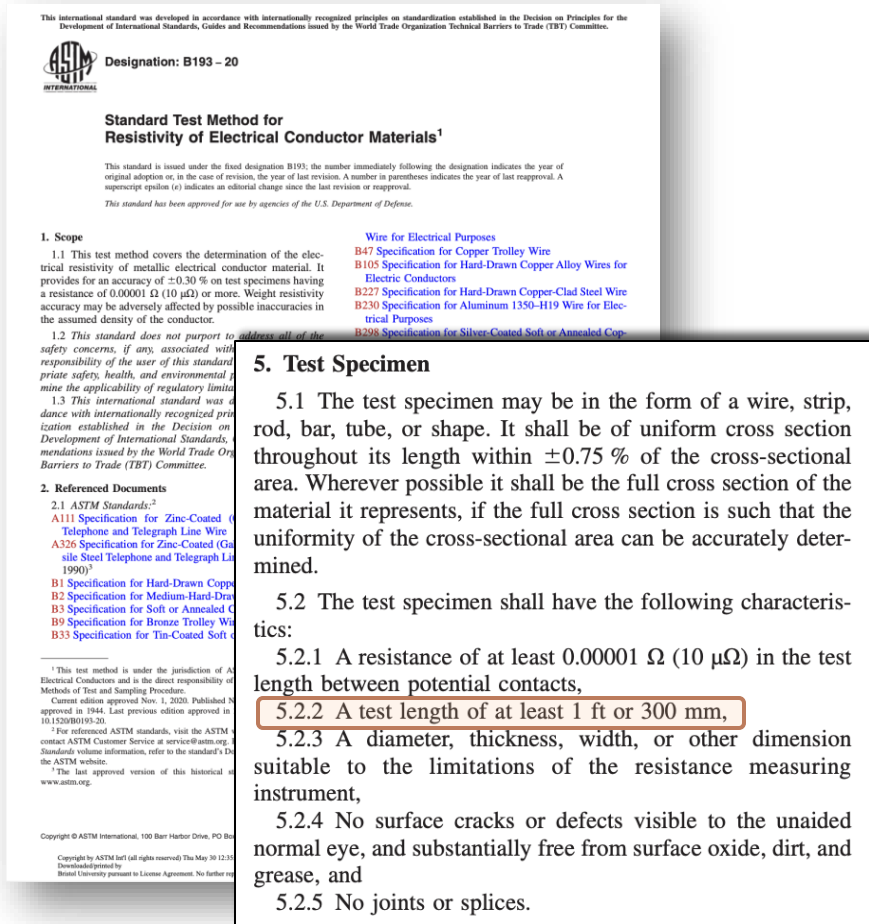
Widely used to measure conductivity of AM components

More suitable measurement method



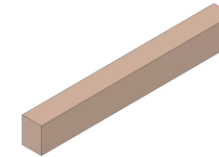
WP2: Measurement Protocol for Electrical Properties

4-Wire Resistance Method:



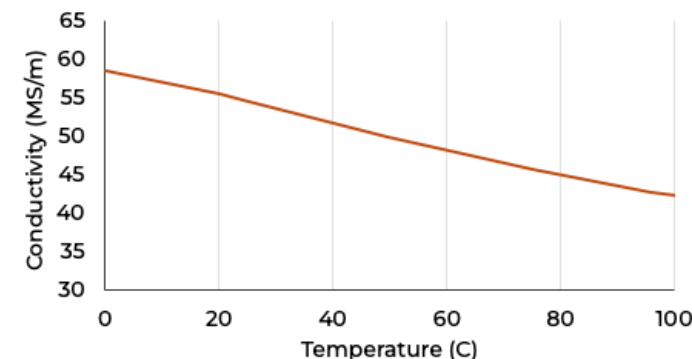
ASTM B193

- ✗ 90% of the reported conductivity of AM components in literature was measured on short bar samples:



2 x 2 x 30 mm

- ✗ None of them report the temperature at which the measurement was conducted, hence it is not valid for direct comparison:





WP2: Measurement Protocol for Electrical Properties

Temperature Coefficient of Resistance (TCR):

- There is no universally accepted standard or method for measuring the TCR
- The standard reference values are used, for copper – $0.00393\text{ }^{\circ}\text{C}^{-1}$ (for 100% IACS Cu at $20\text{ }^{\circ}\text{C}$)
- This value was established in 1910 by testing 37 wrought copper wire specimens of 120 cm in length, under controlled temperature conditions in an oil bath

Standard values for wrought copper should not be assumed for AM components without validation

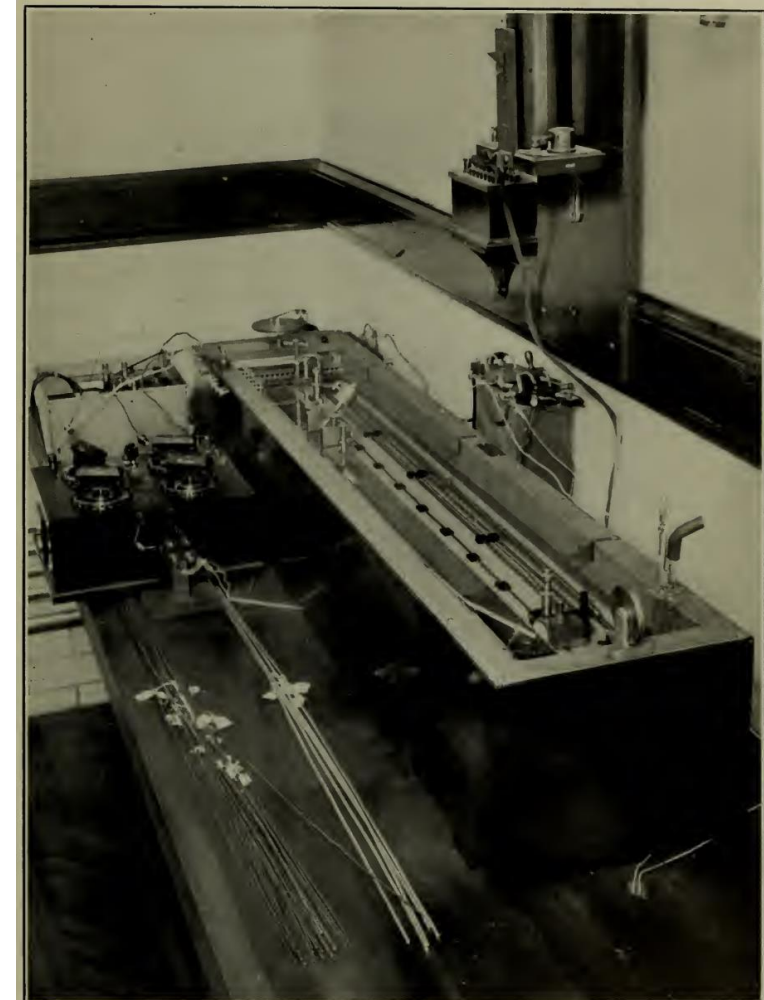


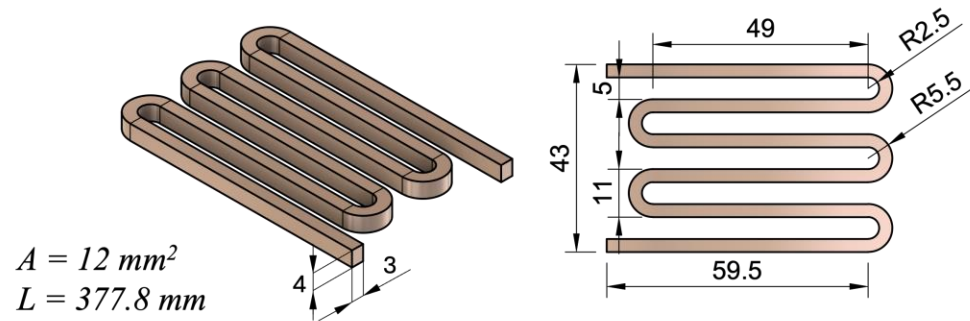
Fig. 3. Conductivity Apparatus.

Wolff F., Dellinger J. (1910)

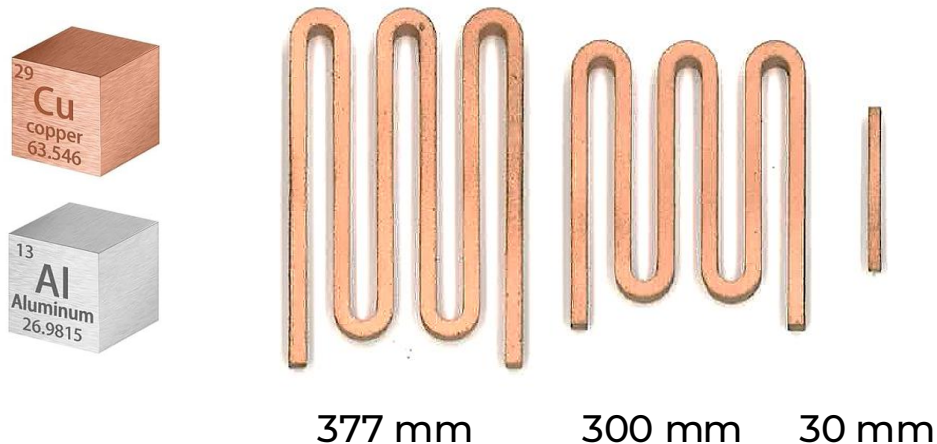


WP2: Measurement Protocol for Electrical Properties

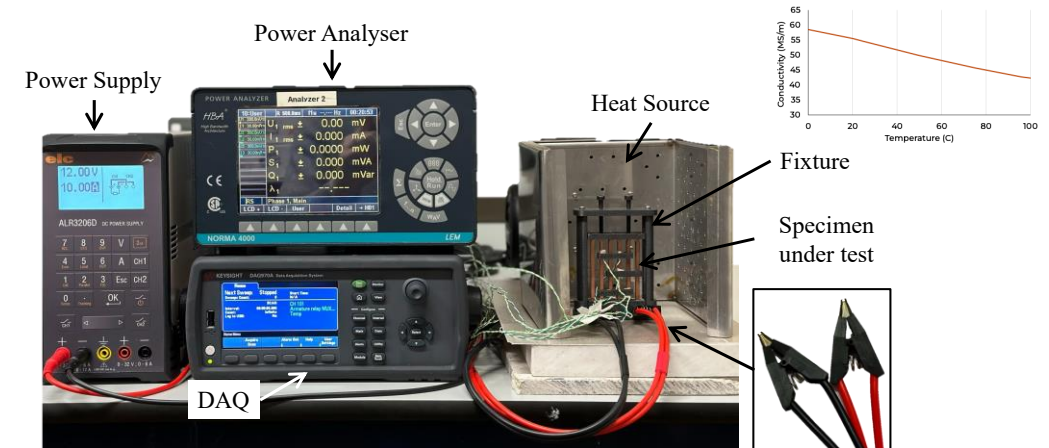
A solution:



1. Sample geometry with a test length $\geq 300 \text{ mm}$



3. Different material and sample length



2. High- and low-current 4-wire resistance measurement setup with commercial-off-the-shelf equipment



4. 3D printed fixtures for different sample designs

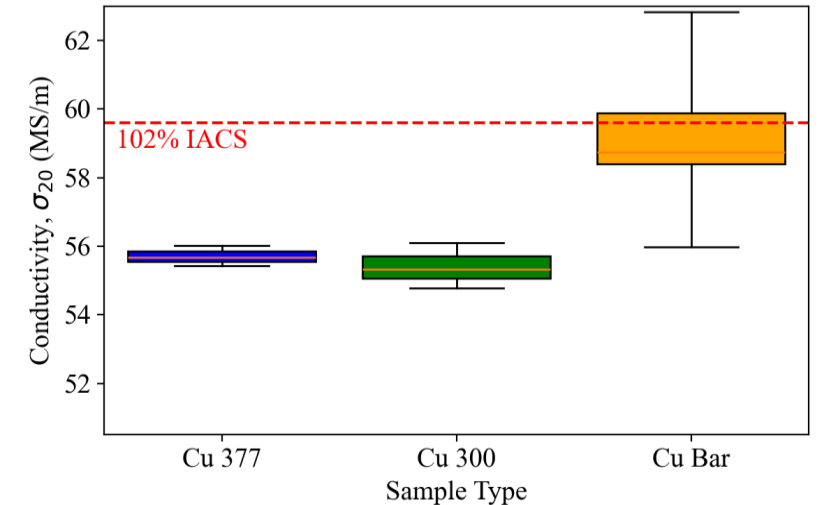
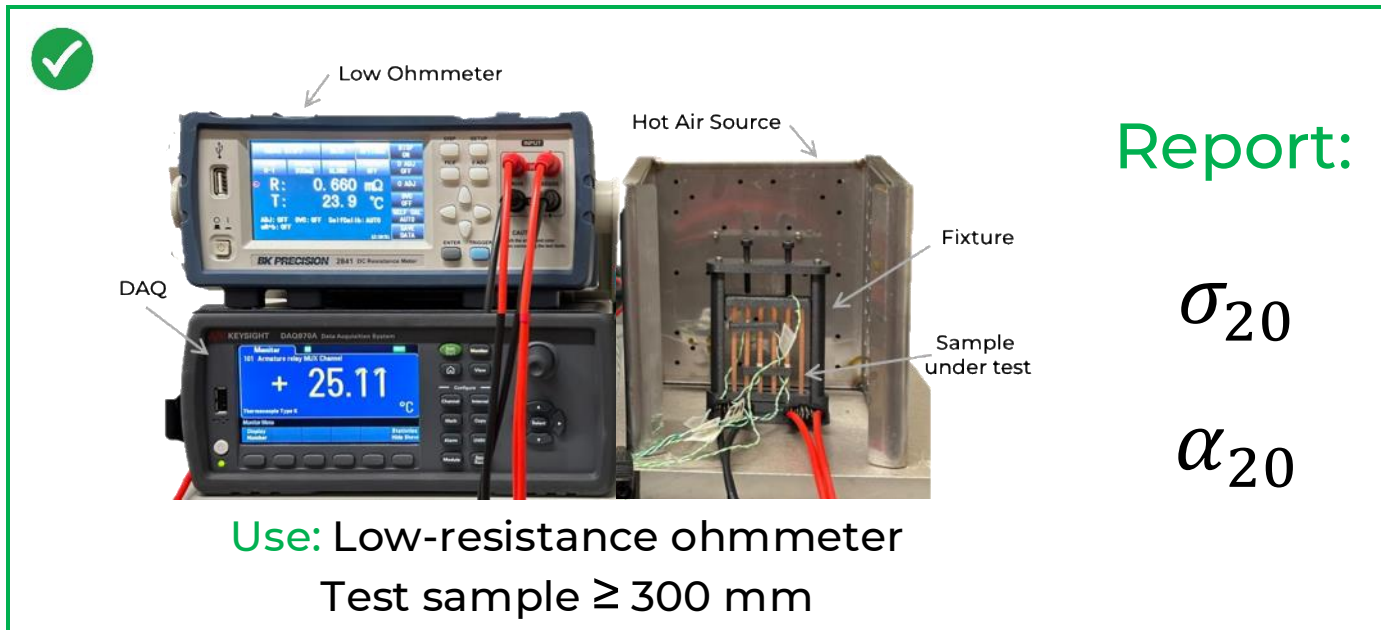


WP2: Measurement Protocol for Electrical Properties

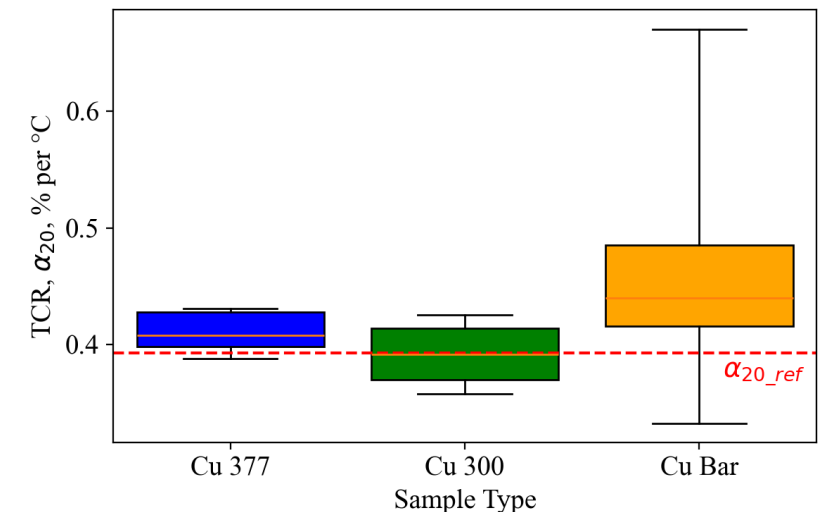
Results:

- A low-resistance ohmmeter provides high accuracy, with a maximum measurement error of 2.2%.
- Longer samples ($\geq 300\text{mm}$) offer higher accuracy in the results.
- Short samples can be used, but dimensional accuracy is critical. Neglecting this can lead to errors up to 17%.

Follow ASTM B193 to generate reliable data for electrical properties of AM materials:



Conductivity of AM CuCP, at 20 °C



TCR of AM CuCP, at 20 °C



WP3: Post-Processes and Electrical Insulation

The Problem:



Aluminium
AM winding



Copper
AM winding

AM coils come without insulation.

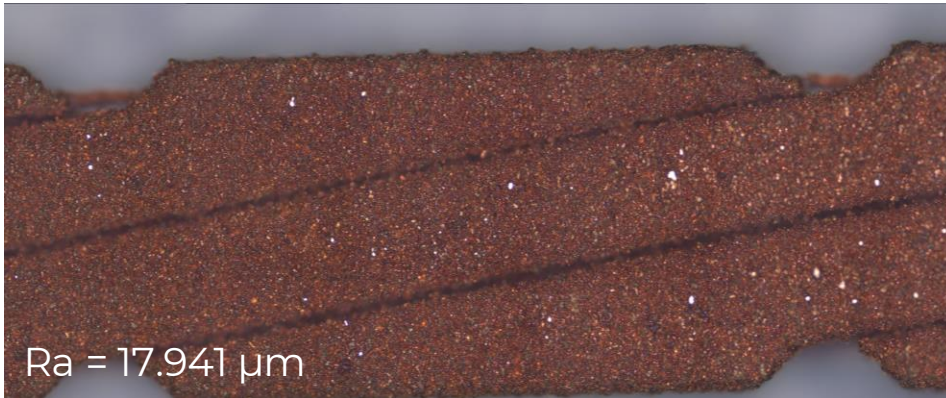
AM components have rough surface finish.

How to prepare the surface and apply robust insulation?



WP3: Post-Processes and Electrical Insulation

Improved electropolishing method for different coil geometries with reproducible results :



Light microscopy images before and after electropolishing



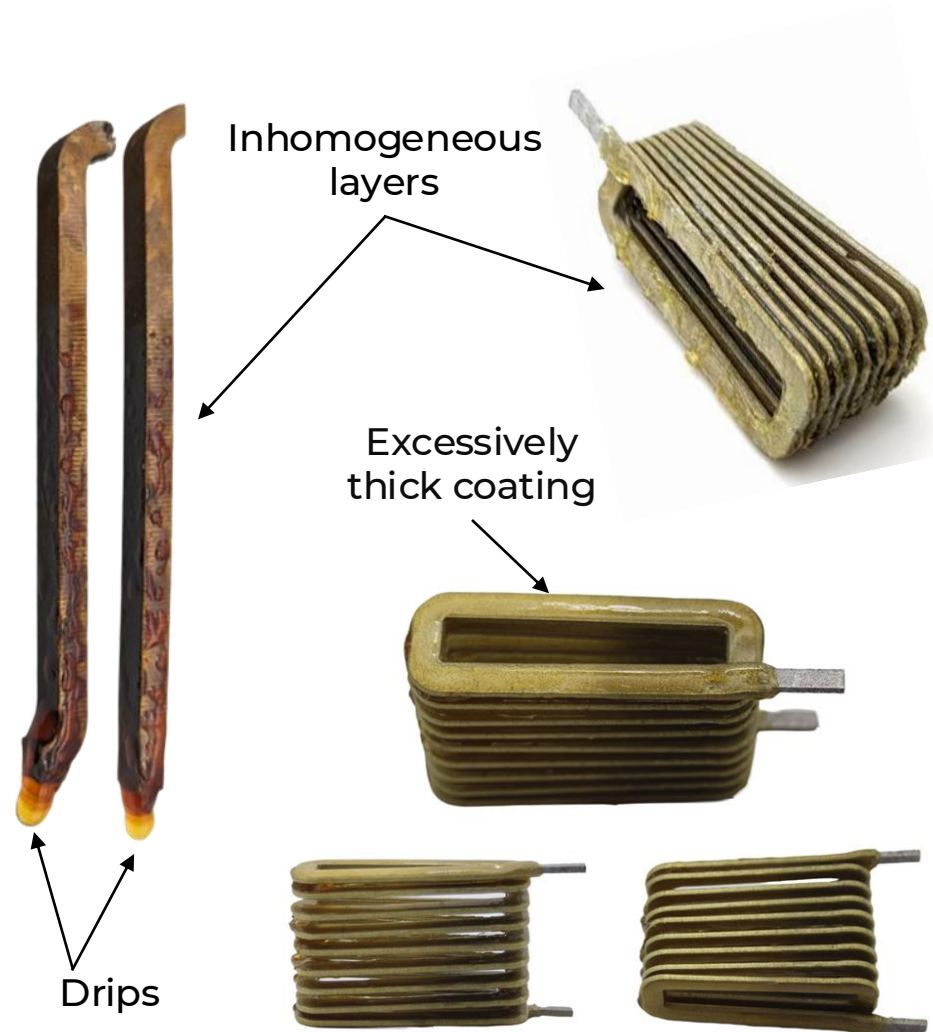
Full shaped profile AM copper coil after electropolishing



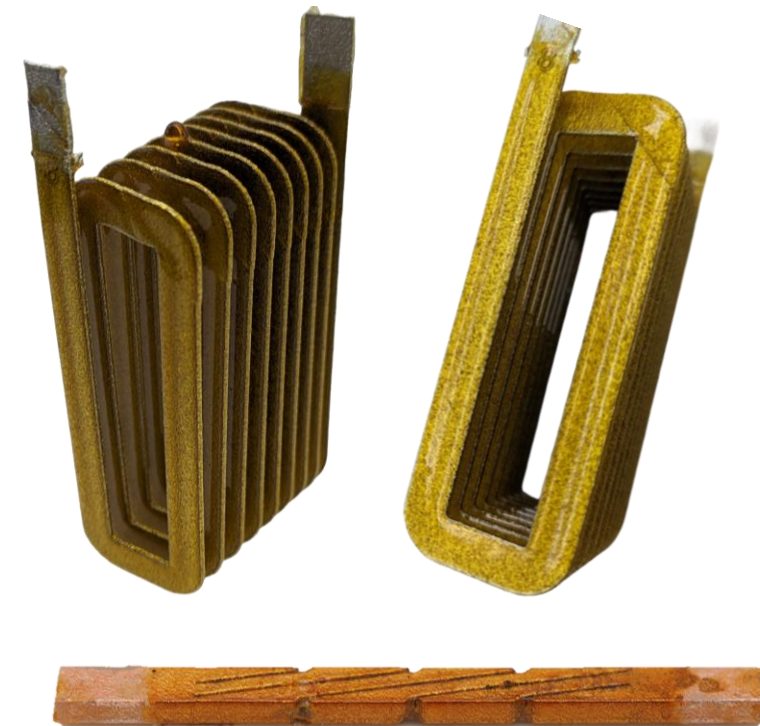
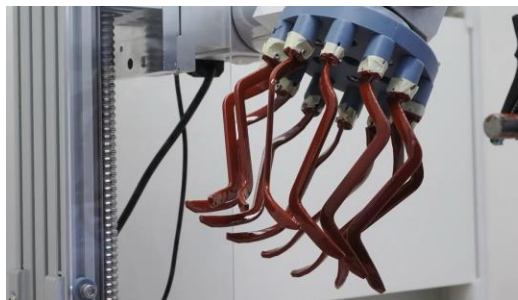
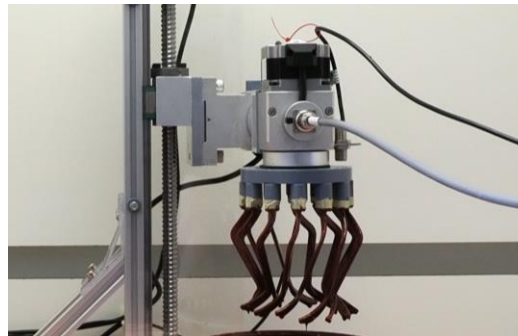
WP3: Post-Processes and Electrical Insulation

Evolution of electrical insulation techniques over time:

Before:



Now:



Improved processes:

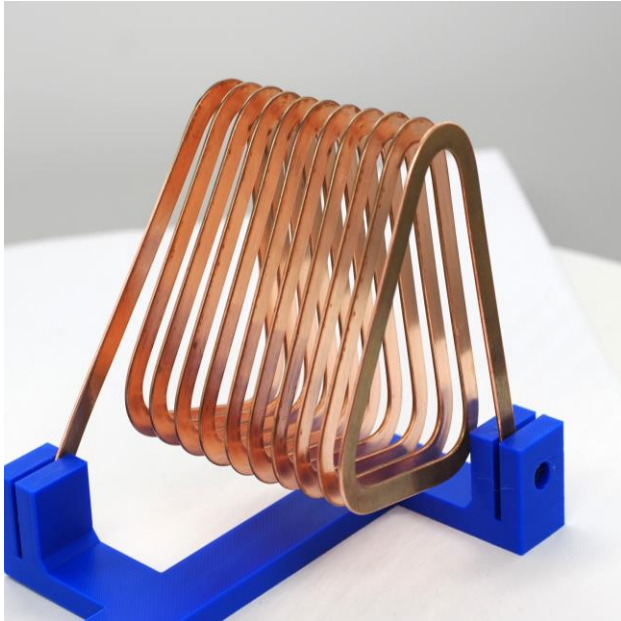
- Automated insulation process
- Better homogeneity and thickness control
- No bubbles, inclusions or drips



WP3: Post-Processes and Electrical Insulation

Exploring new material options: High-performance Thermoplastics and Composite Coatings

Successful PEEK coating trials:



Copper coil before and after electrostatic powder coating with PEEK



Copper coil after melting with uniform coating layer



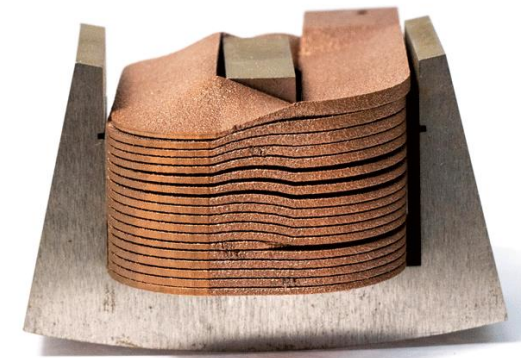
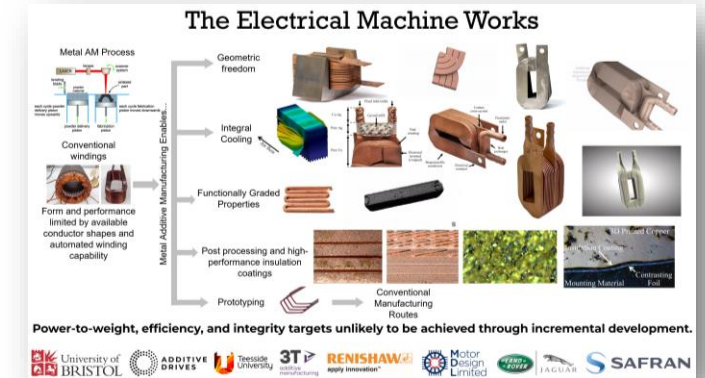
Conclusion

WP1 developed design tools that use AM geometry freedom to create lower-loss winding designs with integrated cooling options.

WP2 established a practical measurement protocol for AM conductors, providing reliable conductivity and TCR data for machine design.

WP3 demonstrated post-processing and insulation routes for complex AM coil geometries, including electropolishing, resin insulation and early PEEK coating trials.

These results demonstrate that high-performance AM windings are achievable when geometry, material characterisation and insulation are developed together — providing a practical route from digital design to manufacturable and functional windings.



CWIEME BERLIN

CELEBRATING
30 YEARS

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Thank you



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Research Associate in Additive Manufacturing
of Electrical Machines



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