

Introduction

Thea Energy, Inc. designed, manufactured, and tested "Canis", a 3x3 array of planar high-temperature superconducting (HTS) rare-earth barium copper oxide (ReBCO) coils for the "Eos" stellarator. Eos, Thea Energy's first integrated fusion system, will mitigate the manufacturing complexity inherent to prior generations of stellarator coils by using arrays of smaller planar coils that will be simpler to manufacture and maintain. To properly shape the magnetic fields necessary for plasma confinement, Eos will require hundreds of these uniform planar coils. Thus, the Canis 3x3 magnet array successfully demonstrated Thea Energy's ability to rapidly scale magnet production while validating and maintaining performance.



Nine fully assembled, instrumented, and validated SMI planar coil-based winding packs mounted to the Canis 3x3 magnet array gravity support assembly, awaiting installation into the Canis cryostat.

Methods

Thea Energy engineers focused their efforts on building up in-house manufacturing and testing capabilities to minimize project timelines and maximize coil iterations and optimizations.

Magnet Manufacturing Capabilities

- 1200 sq foot lab space staffed with a team of trained technicians
- Machine shop capable of producing and inspecting all machined planar coil components (~18 unique parts per coil)
- Orbital tube welding and brazing processes
- Tape solder coating process machines ("Megara" and "Hercules")
- Double pancake winding machine ("Zeus")
- In-wind tape splicing machine ("Orthus")

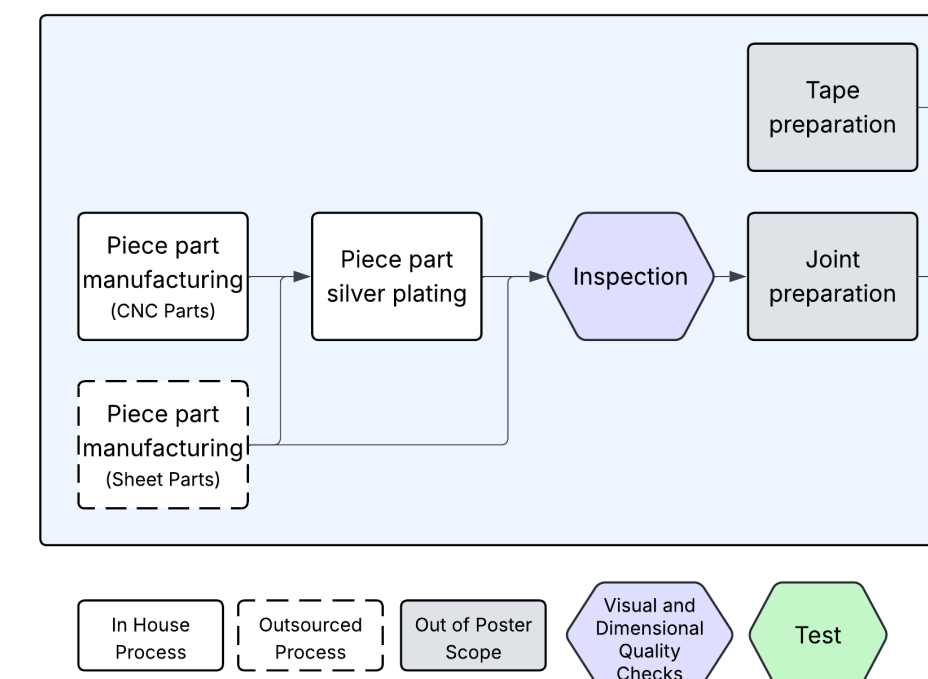
Acceptance Testing Capabilities

- 77K (LN2) instrumentation and test infrastructure ("Castor," "Pollux" and "Hydra") to:
 - Perform acceptance testing of coil components
 - Conduct high-rate QA testing of a single coil double pancake as well as a full Canis winding pack
- Robust data analysis to qualify magnet coils based on Joule heating, current-to-field scaling, radial resistance, etc.

Planar Coil Production and Testing Flow Diagram

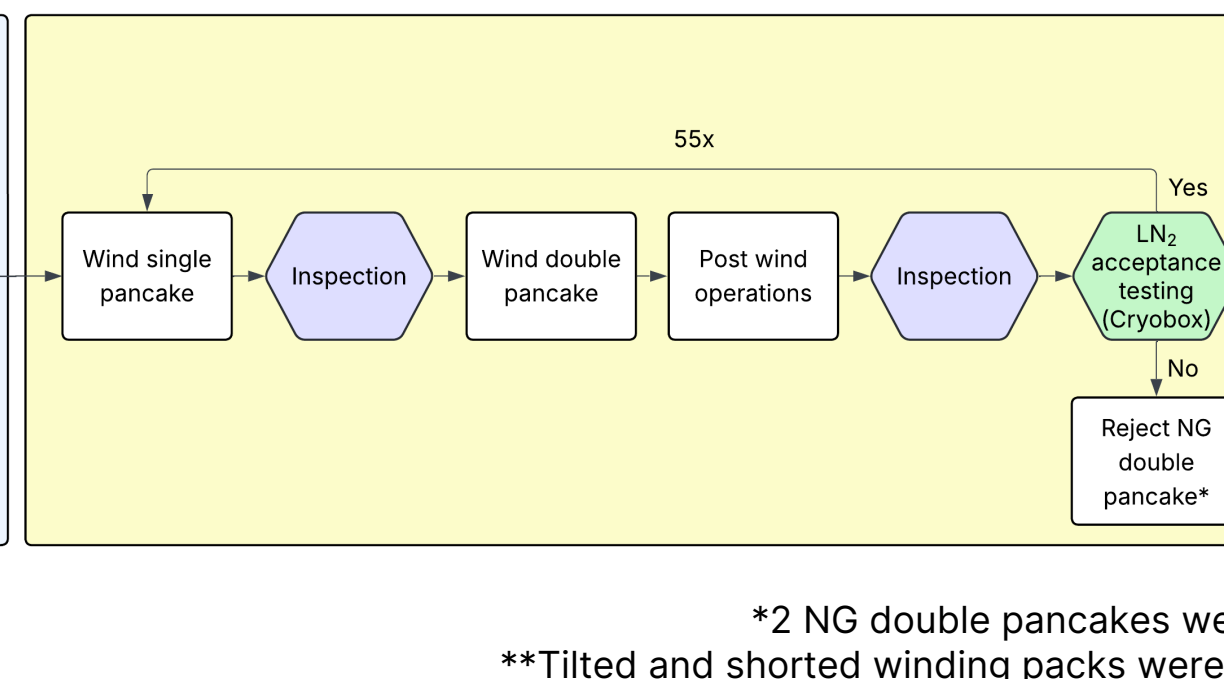
Piece Part Manufacturing

Thea Energy shop expanded in-house capability to build all piece parts including CNC, silver plating, anodizing, orbital with the only exception being sheet metal stamping.



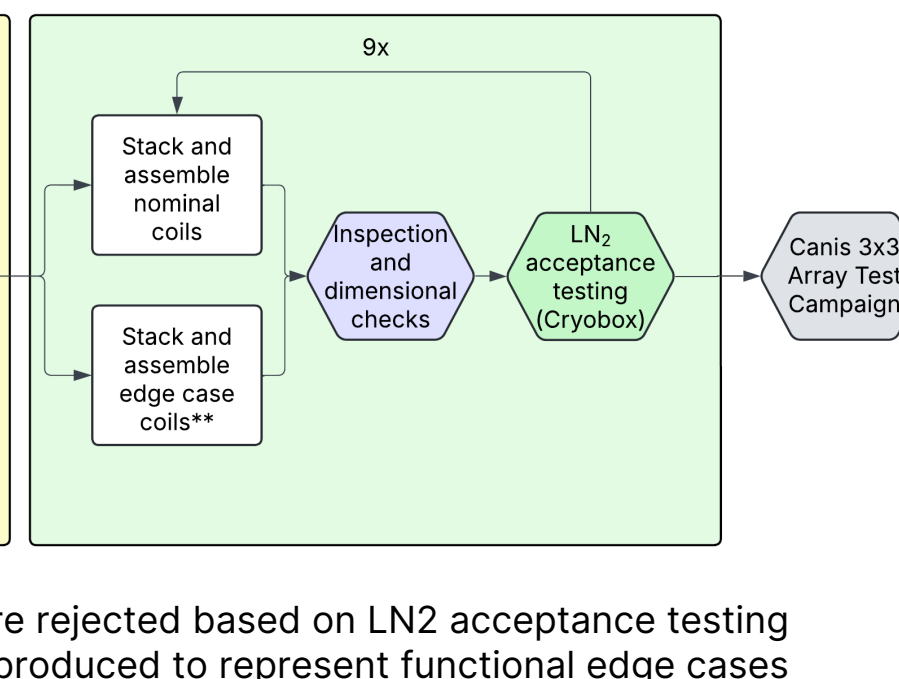
Double Pancake Production and Test

Thea Energy developed custom in-house machines and fixtures optimized for end-to-end production of our unique planar coil design. Included are all necessary tape preparation, winding, quality check and test operation steps.



Planar Coil Assembly and Test

Our planar coil joint design and custom assembly jigs facilitated both nominal and special planar coil stacking. Special winding packs included tilted and shorted configs.

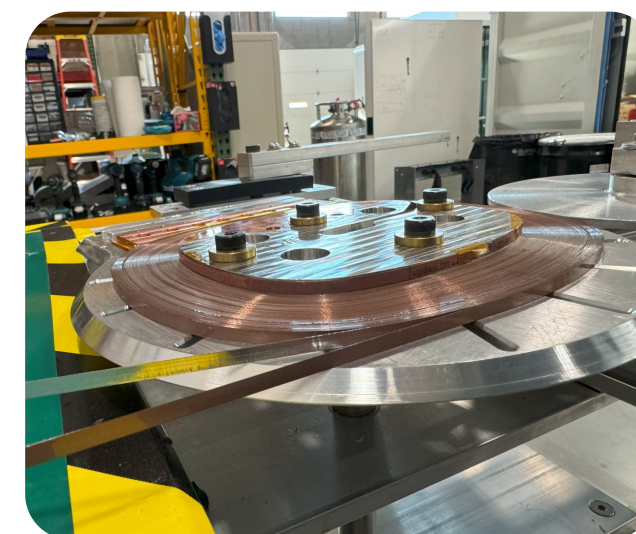
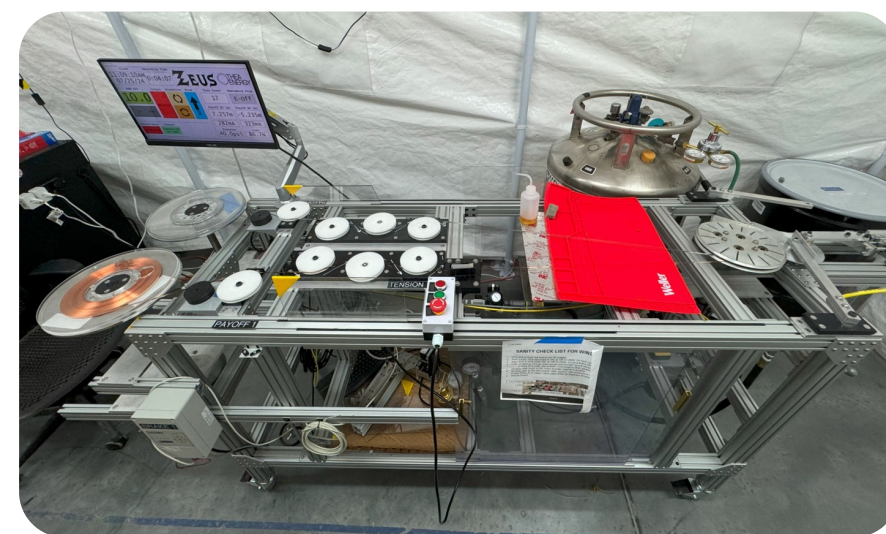


*2 NG double pancakes were rejected based on LN2 acceptance testing
**Tilted and shorted winding packs were produced to represent functional edge cases

Magnet Production Machines

Zeus – Double Pancake Winding Machine

- Active tape tension measurements during wind with feedback loop to winding speed to ensure tape consistency entering coil
- Radial compression roller maintains wind tension and reduces gaps across non-uniform planar coil geometry
- Flexible winding plate geometries to enable winding of both halves of a double pancake on a single machine
- Full integration into Thea Energy test data repository for real time wind data capture



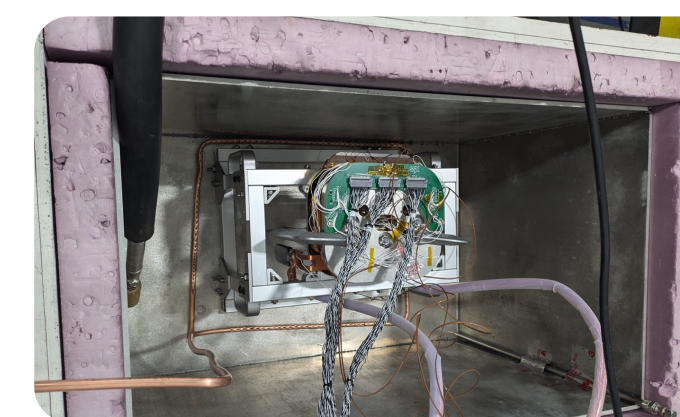
Orthus – Splicing Machine Built Into Zeus

- Enables removal and rework of tape defects during wind process
- Various temperature profiles allow for splicing of various tape and solder combinations

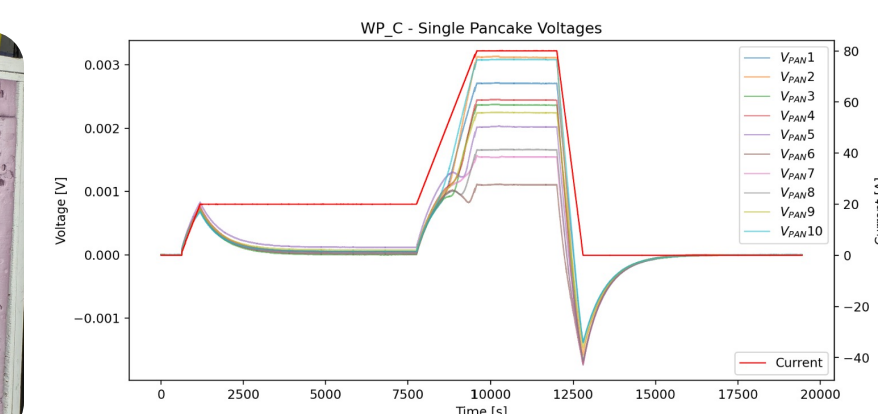
Magnet Testing and Validation

Hydra, Castor, Pollux – Fully Instrumented LN2 Cryoboxes

- 77K LN2 testing capabilities include HTS sample testing, joint testing, single coil and winding pack acceptance testing
- Magnet coil and winding pack instrumentation
 - Hall effect sensors for field measurements
 - Various individual coil voltage measurements
 - Inter and intra double pancake joint voltage measurements
 - Temperature measurements using Cernox® RTD's and thermocouples
- Test article submerged in a bath of LN2 and tested with current ramps past its expected transition current
- Data analysis code to calculate radial resistance, equivalent series resistance and I-B scaling of both a single magnet coil and a winding pack



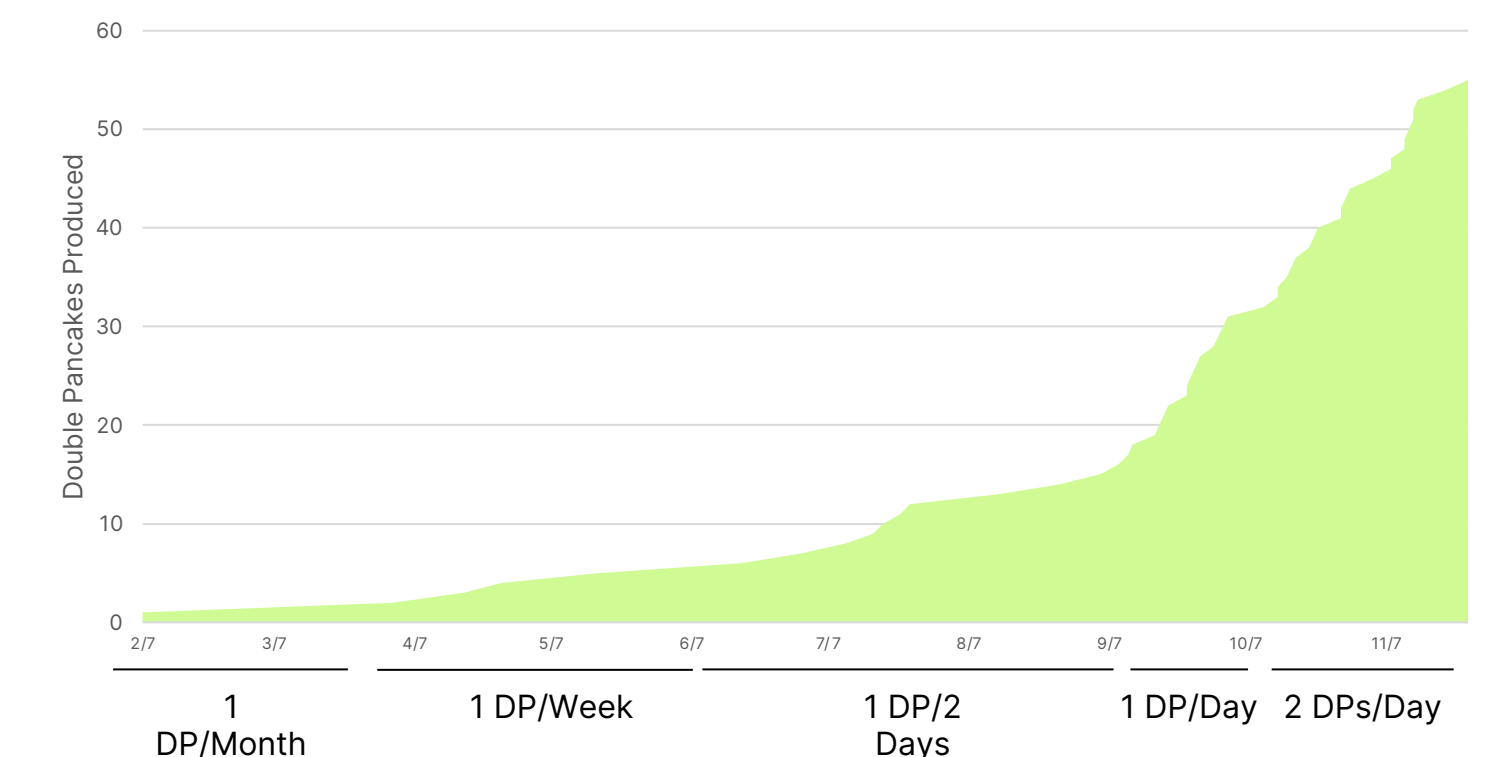
Cryobox used for LN2 QA testing.



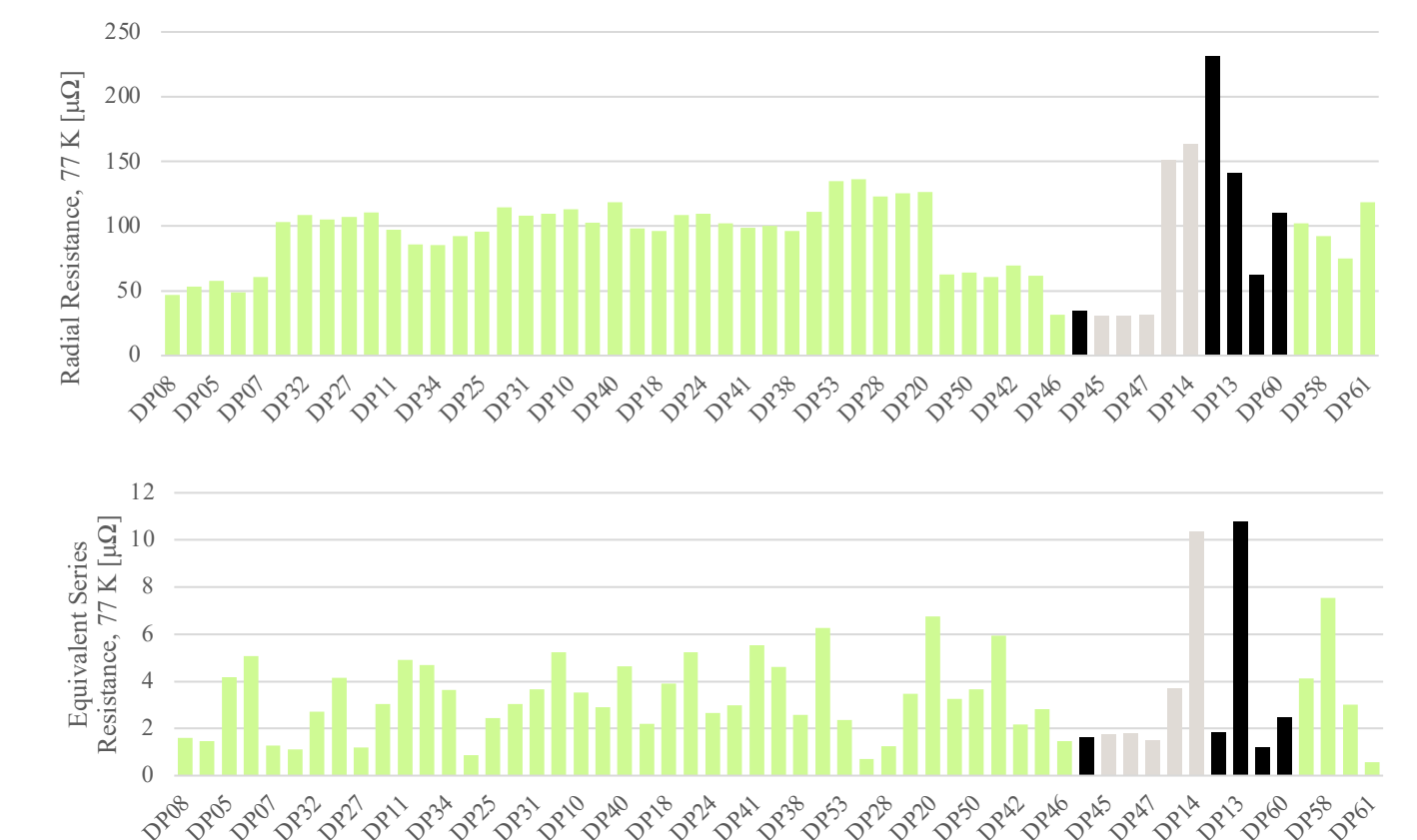
Typical voltage response of winding pack "pancakes" to a current ramp test.

Production and Testing Data

Canis Double Pancake Production and Testing Over Time



Ramp curve for Canis planar coil double pancake testing. Starting at 1 DP/month as the team initially explored planar coil designs, production peaked at 2 DPs/day.



Radial resistance and equivalent series resistance values calculated for all Canis DP's, where green, black and grey represent different HTS tape manufacturers used in winding these magnet coils.

Conclusion

The Thea Energy team successfully ramped a manufacturing and testing pipeline that produced 55 functional double pancakes. These double pancakes were then assembled into 10 HTS ReBCO planar coil winding packs for the Canis 3x3 magnet array. This effort has helped to de-risk major portions of the future technical and operational challenges in the development of the Eos Stellarator, the Company's first integrated stellarator system.