THEA ENERGY

[Thu-Mo-Po.04-04] Zethus: a prototype HTS planar shaping coil for the Eos stellarator

K. Tang, B. Berzin, B. Chen, C. Chen, M. Dickerson, A. Doudna Cate, D. Gates, D. Guan, W. Harris, W. Kalb, U. Khera, B.D. Koehne, T. Kruger, A. Menon, D. Nash, S. Noronha, R. Powser, A. Saucedo Basurto, M. Slepchenkov, S. Srinivasan, C. Swanson, K. Tamhankar, A. van Riel, W.S. Walsh, J. Wasserman

Introduction

To generate twisted magnetic fields, stellarators have historically required complex and precise modular coils, which are difficult to manufacture and maintain. As an alternative approach which mitigates this challenge, Thea Energy, Inc. is developing "Eos", a planar coil stellarator that can shape the needed fields using hundreds of smaller and more easily manufactured coils. As the first step to Eos, we launched the "Zethus" program to demonstrate a prototype high-temperature superconducting (HTS) shaping coil.

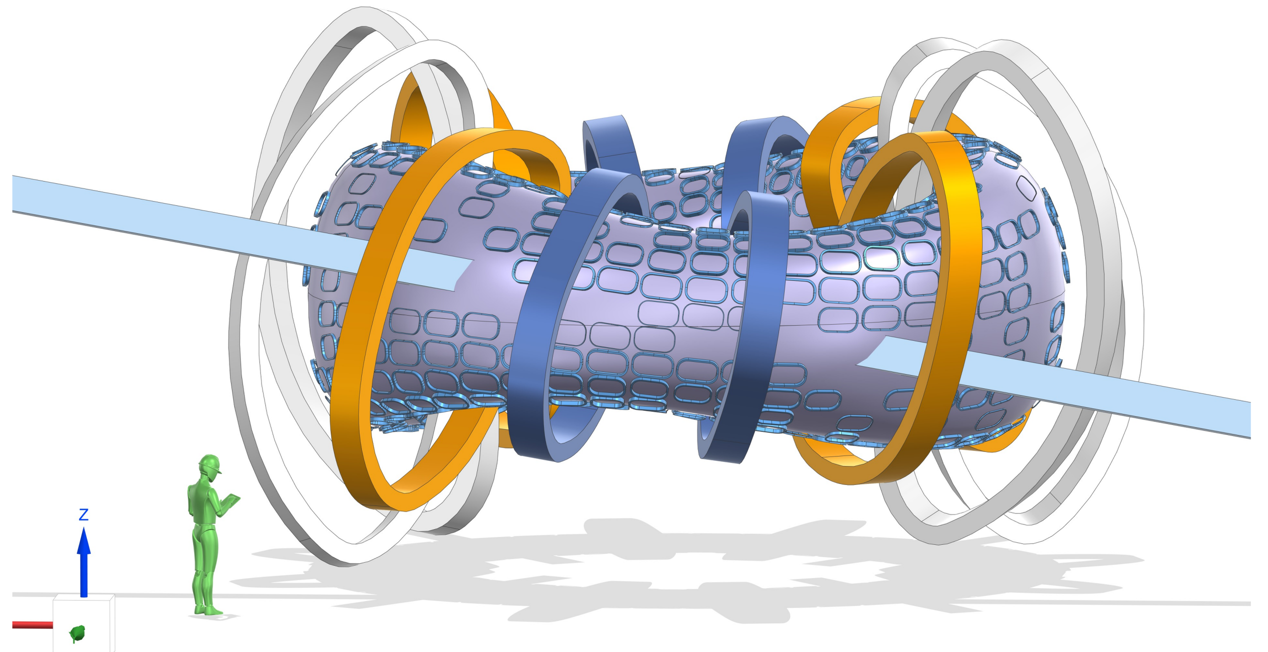

Figure 1. Rendering of the Eos planar coil stellarator [1]. Planar plasma-encircling coils are shown in white, orange, and blue. Planar shaping coils are shown as rounded rectangles.

Coil Design

Table 1 – Coil Specifications

Operating current	150 A	**Stored energy**	4.4 kJ
Operating temperature	20 K	**Peak field on conductor**	3.7 T
Number of pancakes	10	**Peak field in bore**	1.8 T
Total current	225 kA-turns	**Fraction of critical**	~28%
Current density	180 A/mm²	**Coil architecture**	Soldered, metal-insulated

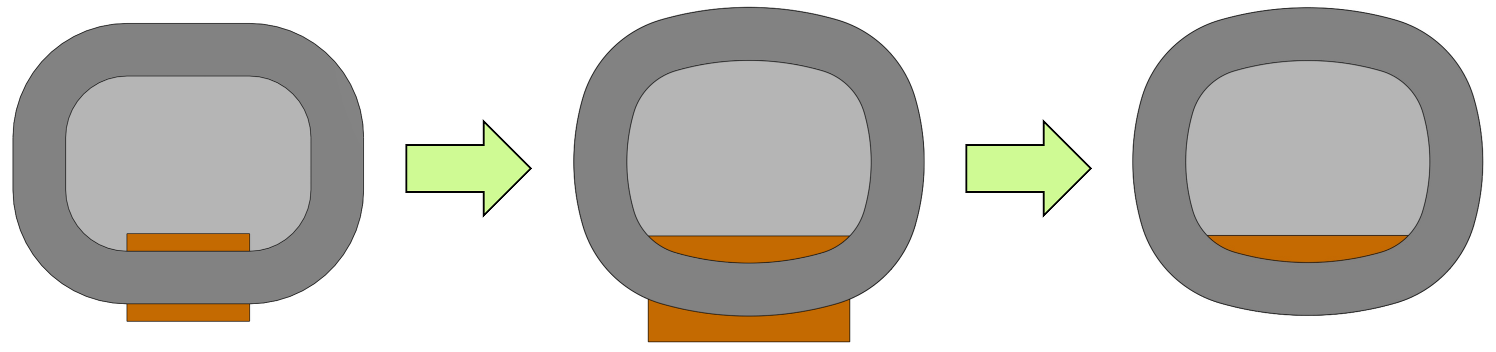

Figure 2. Design iterations of the Zethus magnet. The stainless-steel core is shown in light grey, the winding is shown in dark grey, and resistive joints are shown in orange. Not to scale.
(Left) Version 1: Rectangular racetrack with both resistive inner and outer joints.
(Middle) Version 2: Rounded rectangle with both resistive inner and outer joints.
(Right) Version 3: Rounded rectangle with resistive inner and superconducting outer joints.

Coil Integration

After five HTS double pancake winding layers were individually manufactured and acceptance tested in LN2, the coil was assembled…

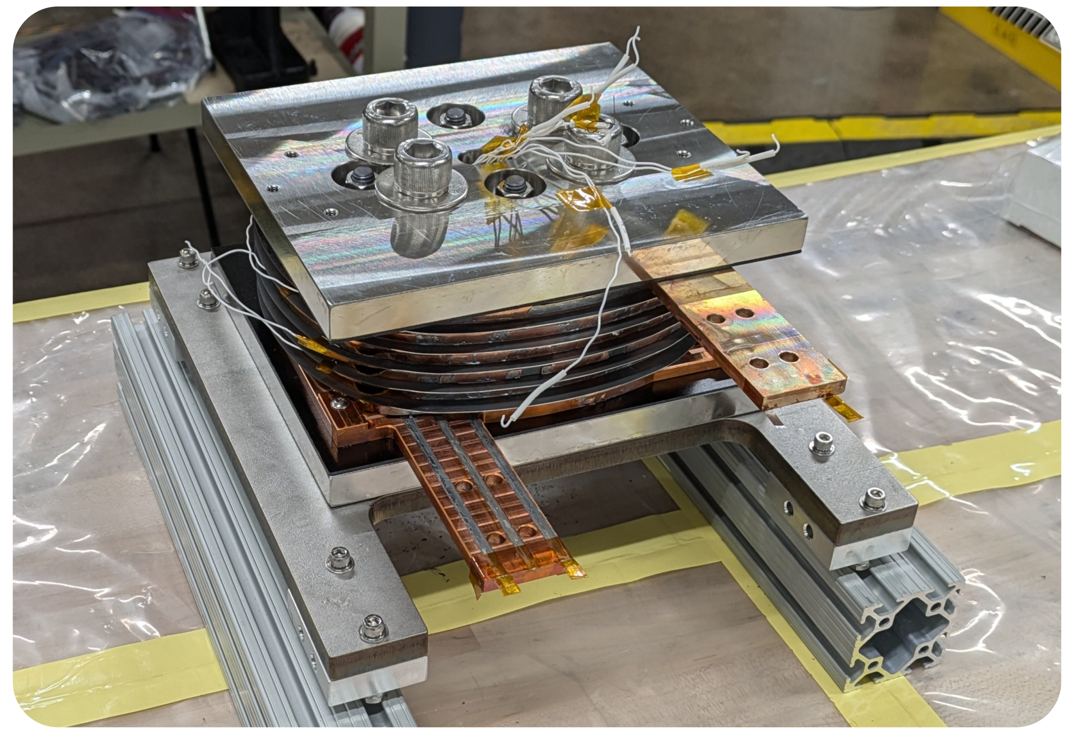

Figure 3. The Zethus winding pack after being fully assembled on the bench.

…and installed into a custom cryostat.

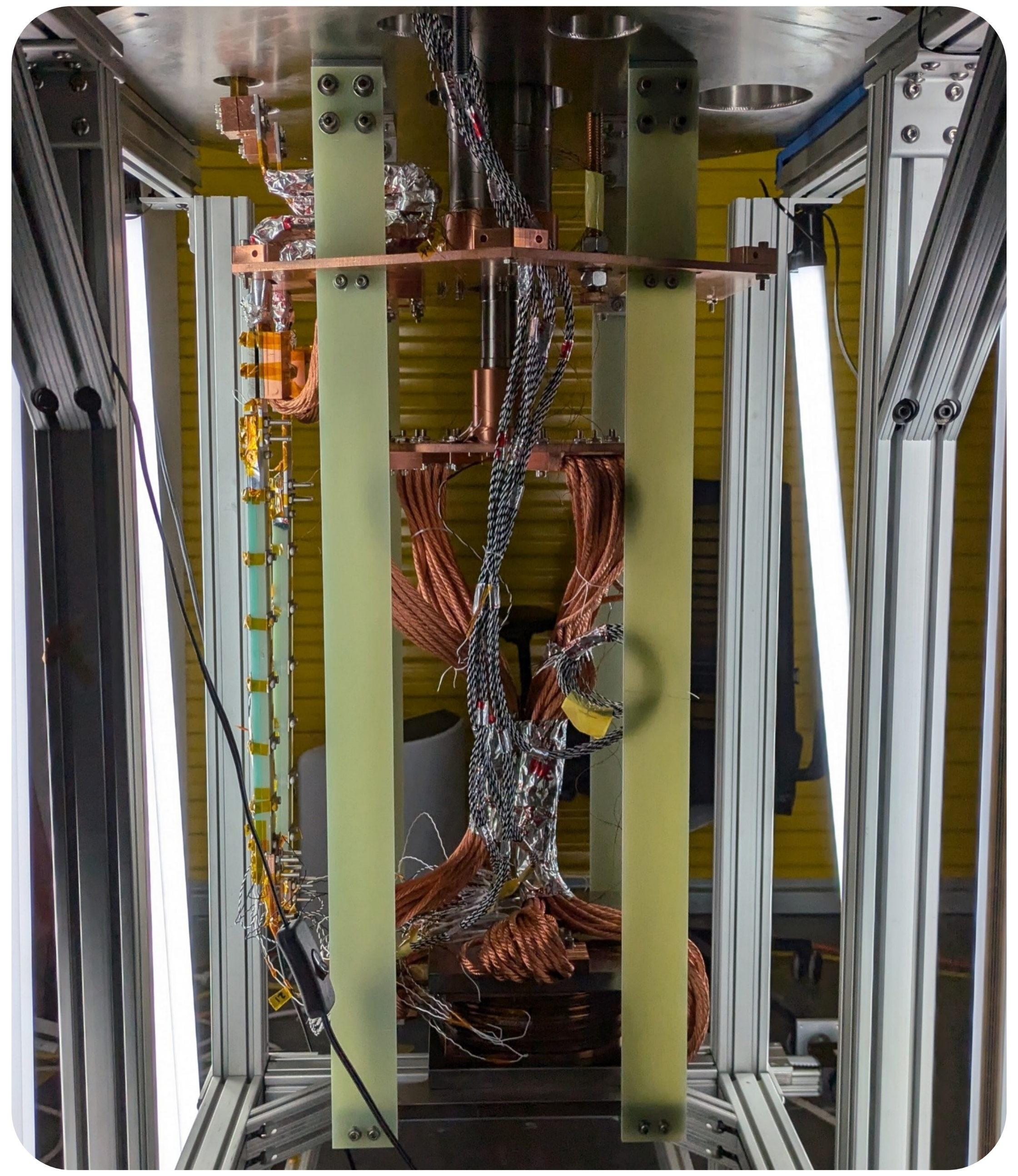

Figure 4. Completion of winding pack installation and instrumentation. The Zethus cryostat lid held a two-stage cold head, copper current leads, and gravity support bars. The first stage anchored a thermal shield (not pictured) and the HTS current leads' warm ends. The second stage anchored the magnet and the HTS current leads' cold ends.

20 K Test Campaign – Coil Characterization

The Zethus test campaign began with a series of current steps to validate the magnet's steady-state and current-dependent behavior.

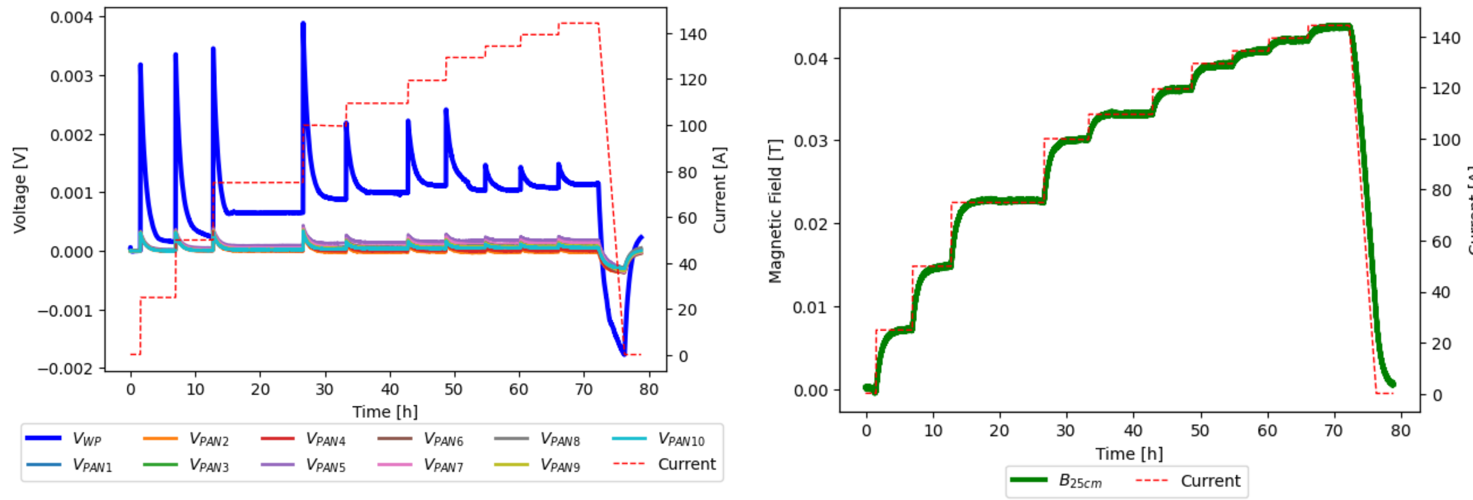

Figure 5. Current-stepping test data. At this stage, the final step to 150 A was omitted due to insufficient thermal margin on the HTS current leads.
(Left) Winding pack and individual pancake voltages with corresponding currents.
(Right) Magnetic field measured 25 cm from the coil's center axis with corresponding currents.

To demonstrate a 0 to 0.0300 T field ramp at 25 cm from the coil midplane in 30 minutes, the magnet was held at a higher-than-operating current of 225 A for 30 minutes and then reduced to 100 A, resulting in a near flat-top in field.

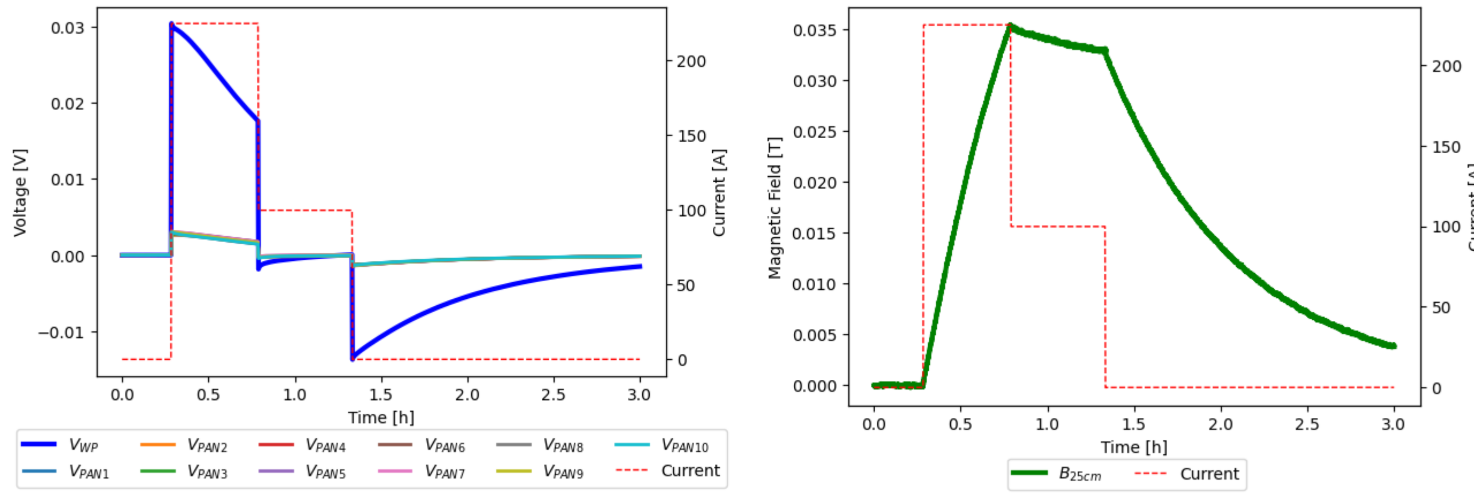

Figure 6. Field-ramping test data.
(Left) Winding pack and individual pancake voltages with corresponding currents.
(Right) Magnetic field measured 25 cm from the coil's center axis with corresponding currents.

20 K Test Campaign – Thermal Cycling

The magnet was then subjected to a series of thermal cycles to characterize any potential performance degradation from warm-up and cooldown.

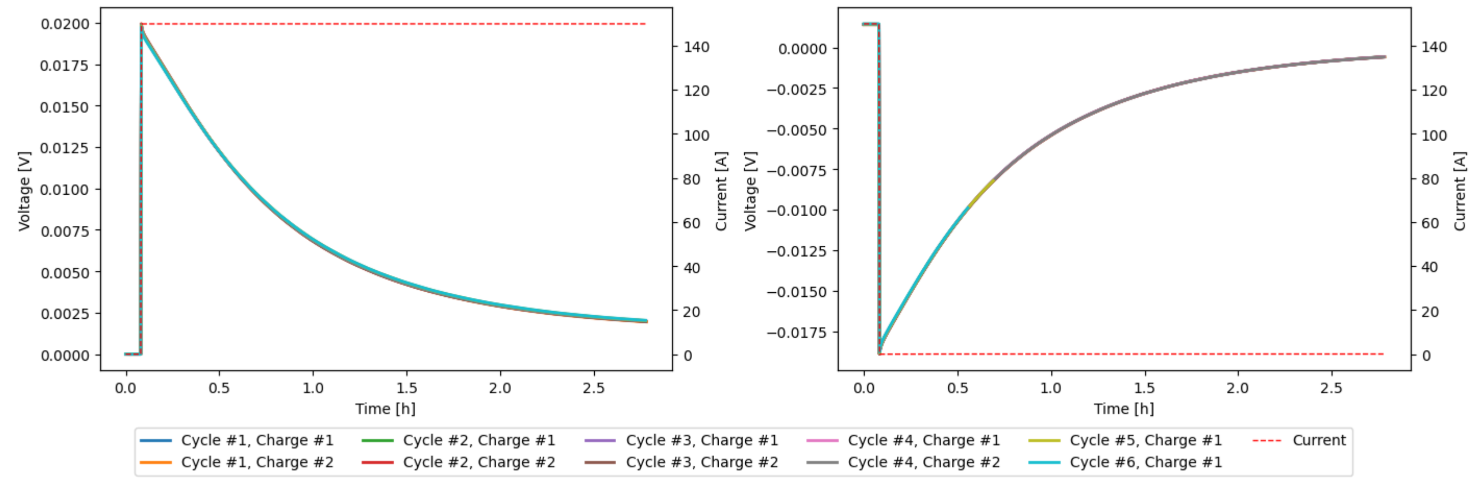

Figure 7. Thermal cycle test data. Over the 6 cycles, the coil's radial resistance decreased by 0.9% and its equivalent series resistance increased by 3.0%.
(Left) Winding pack voltages when current was stepped to 150 A in each cycle.
(Right) Winding pack voltages when current was discharged after settling in each cycle.

20 K Test Campaign – Quench Characterization

Finally, in attempts to induce a quench, transitions through the coil's critical current (36 A) at 77 K and critical temperature (59 K) at 150 A were tested.

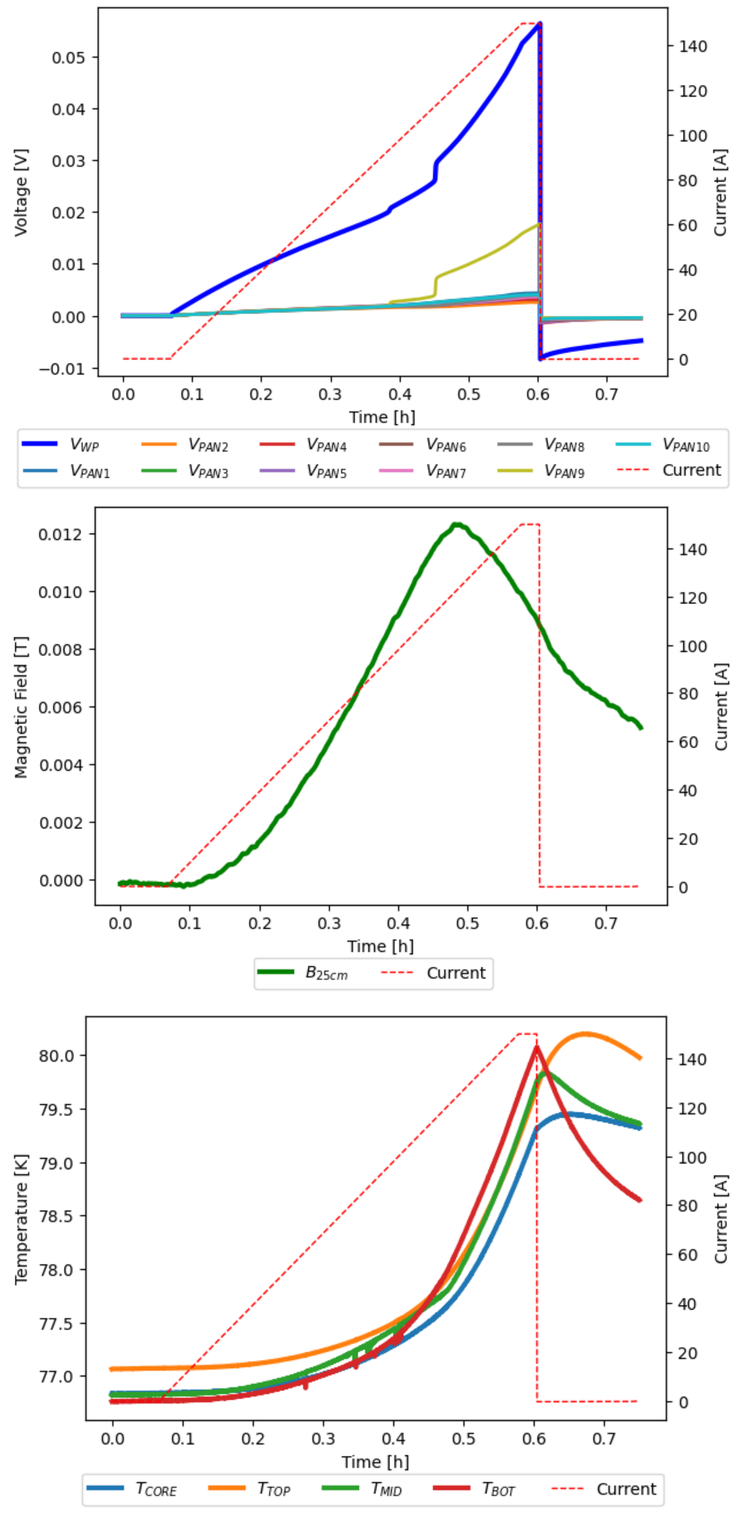

Figure 8. Attempted current quench test data. The coil was held at 77 K and ramped through its critical current of 36 A to 150 A and held until a thermal runaway occurred in an outer joint.
(Top) Coil voltages.
(Middle) Magnetic field at 25 cm from coil center.
(Bottom) Coil temperatures.

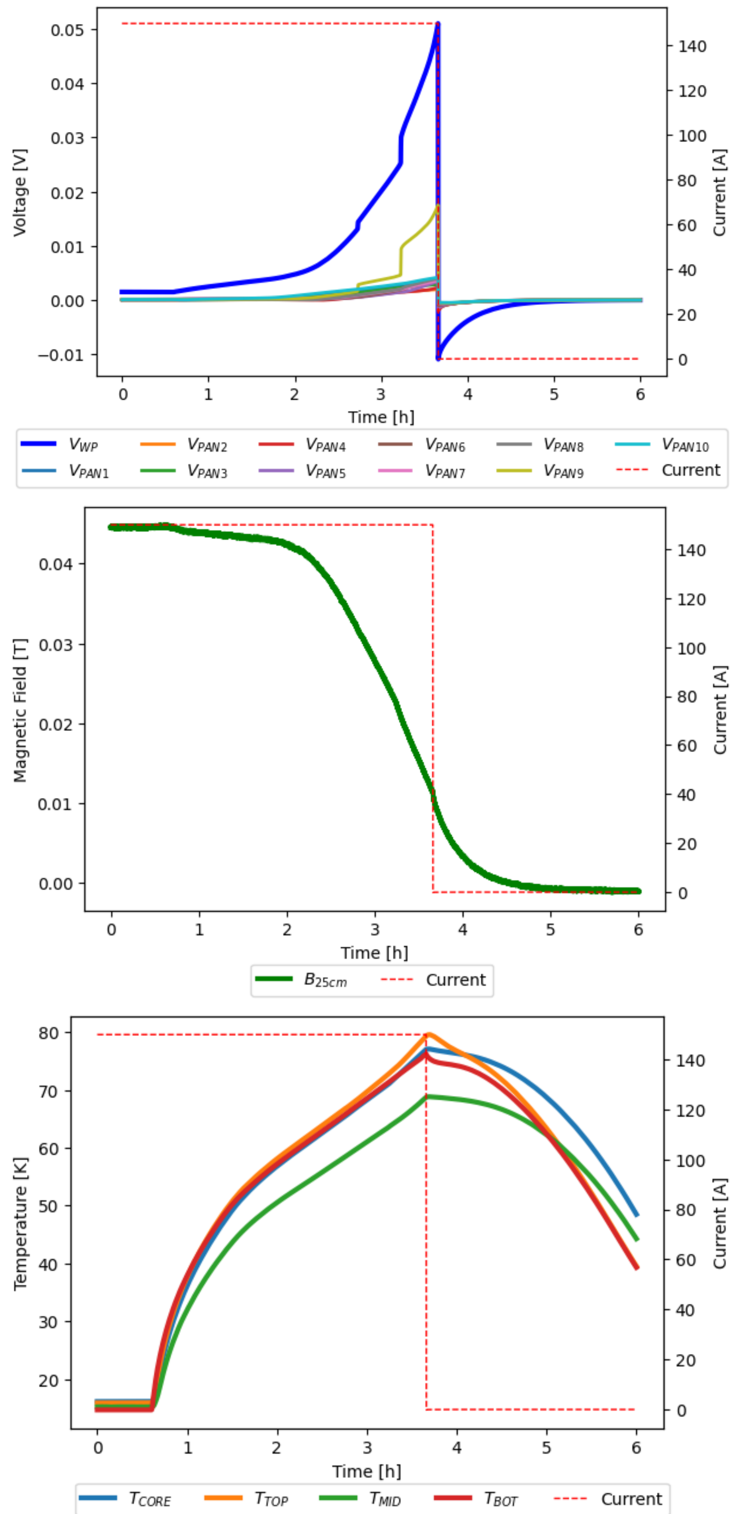

Figure 9. Attempted temperature quench test data. The coil was held at 150 A and warmed through its critical temperature of 59 K until a thermal runaway occurred in an outer joint.
(Top) Coil voltages.
(Middle) Magnetic field at 25 cm from coil center.
(Bottom) Coil temperatures.

In both tests, only PAN9 showed a sudden discharge with no inductive cascade to the other pancakes, thus demonstrating a slow thermal transition to normal conduction instead of a rapid quench. As such, the coil was quench-resistant and displayed no noticeable performance degradation after testing.

Conclusion

Through the test campaign, the Zethus prototype coil maintained robust and consistent performance, therefore opening the path to the "Canis" 3x3 array of HTS planar coils and to the Eos stellarator [2].

[1] Swanson, C.P.S., et al. (2025). The scoping, design, and plasma physics optimization of the Eos neutron source stellarator. Nuclear Fusion, 65(2), 026053.
[2] Nash, D., et al. (2025). Prototyping and Test of the "Canis" HTS Planar Coil Array for Stellarator Field Shaping. https://arxiv.org/abs/2503.18960

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Also check out Sat-Mo-Or2-02: Prototyping and test of the Canis 3x3 magnet array for stellarator field shaping!

www.thea.energy
info@thea.energy