Prototyping and Test of the “Canis” 3x3 Magnet Array for Stellarator Field Shaping

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MAGNET TECHNOLOGY 29

THEA ENERGY

2025

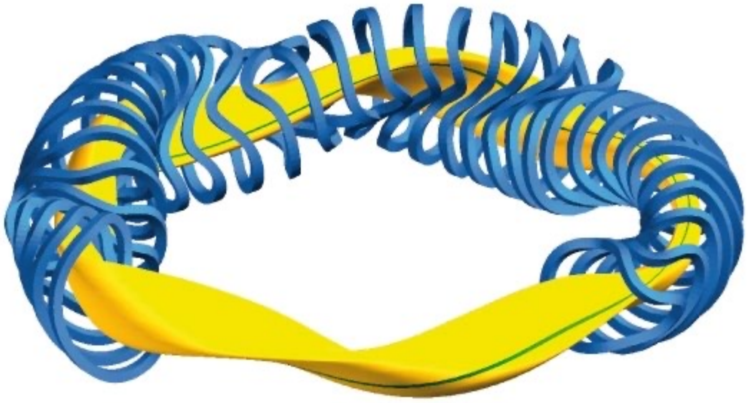
Thea Energy Poster Presentations at MT29

Wed-Af-Po.01-03	Canis: 3×3 array of sub-scale planar coils for the Eos stellarator	Brian Chen
Thu-Mo-Po.04-04	Zethus: a prototype HTS planar shaping coil for the Eos stellarator	Kevin Tang
Thu-Mo-Po.09-02	Instrumentation of the Canis 3×3 superconducting magnet array	Matthew Dickerson
Thu-Af-Po.05-01	High-rate production and validation of Canis magnets	Ketaki Tamhankar Tommy Ikuss
Thu-Af-Po.07-03	Quench simulations of a 3×3 field shaping NI HTS coil array for a planar coil stellarator	Jamal Olatunji
Fri-Af-Po.03-04	The design and performance of the Canis 3×3 magnet array support systems	Milo Korman

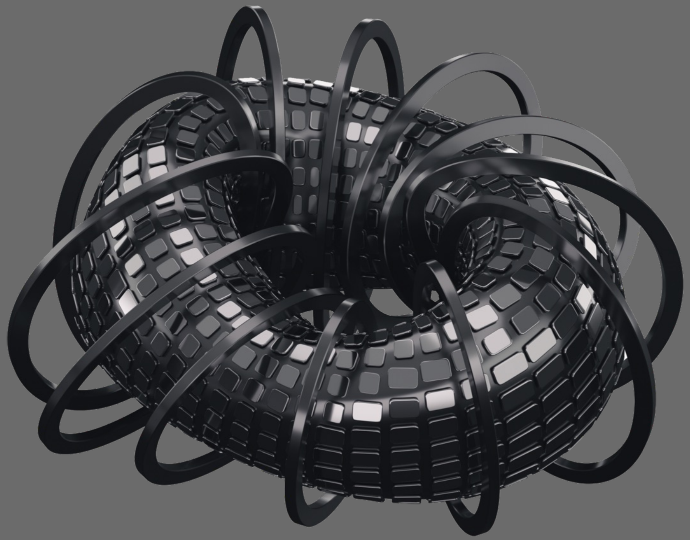
We've Eliminated Complicated & Costly 3D Stellarator Magnets

Prior 3D magnet coil stellarator architecture

W7-X, Germany[1]



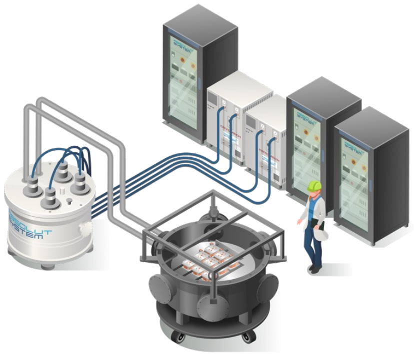
Thea Energy programmable magnet array stellarator architecture

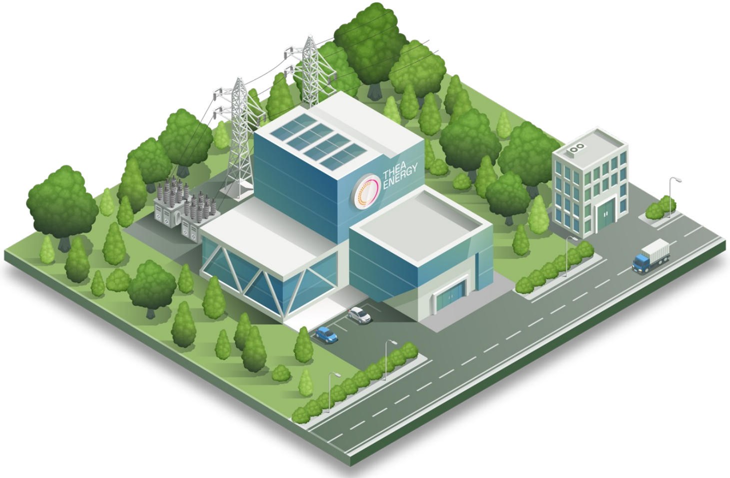


Faster & less costly to manufacture, construct, and operate

1. Wendelstein 7-X, 2010, Max-Planck Institut für Plasmaphysik, https://www.ipp.mpg.de/w7x.

Pathway to Electricity on the Grid





2025

2030

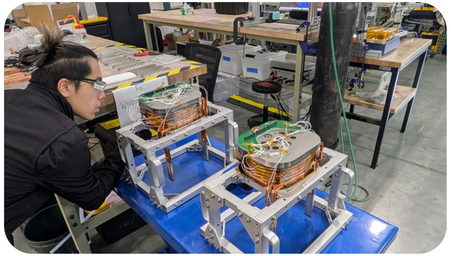
Prototyping core tech

Eos large-scale integrated stellarator

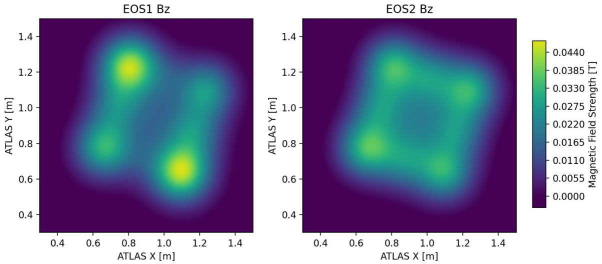
Helios pilot plant

“Canis” Magnet Array Program Goals

- Build 10 shaping coil Winding Packs (WP)
  - Double Pancake (DP) production ramped to ≥ 1 DP/day
  - DP production time < 4 days including acceptance test
  - Demonstrate insensitivity to HTS supplier
- Demonstrate field shaping capability
  - Closed-loop control of $\mathbf{B_Z}$ at each magnet
  - Reproduce several field shapes with ≤ 1% RMS field error
  - Validate field shapes with 2D scan 25 cm from array midplane
- Eos scenario development
  - Demonstrate controlled transition between field shapes
  - Simultaneously discharge full array
  - Show **non-propagation** and **non-damage** from quench
  - Show insensitivity to manufacturing and assembly variation
- Develop Eos design criteria



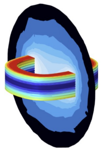
Two Canis WPs in LN2 test configuration



Eos-relevant field shapes measured on scanning plane

“Tilted” magnet demonstrating tolerance to assembly defects

Canis Shaping Coil Design



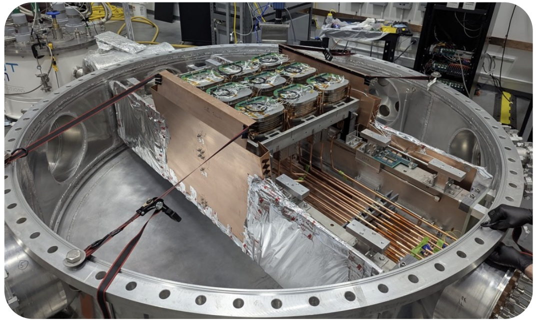
- Planar coil stellarator design drivers
  - ~200 A/mm^2 in >14 T total field
    ↳ **REBCO SUPERCONDUCTOR**
  - ~1,000 current leads for planar coil stellarator
    ↳ **LOW CURRENT**
  - DC operation, minimal charging or field quality constraints
    ↳ **NON-INSULATED**
  - Defect tolerance, passive quench protection
    ↳ **NON-INSULATED**
  - Stable radial resistance and structure over long cycle life
    ↳ **IMPREGNATED WINDING**

- Array experience >> optimizing coil
  - Move to array fast with a viable magnet design
  - Design coils for high margin and low risk
  - Accept most "defects" if minimal impact to 20 K operation

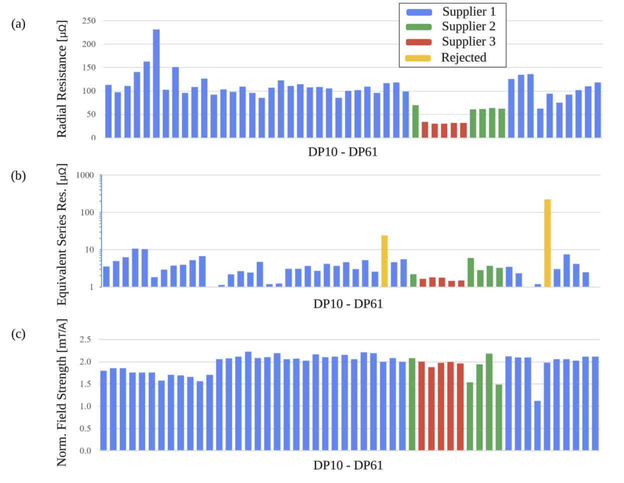
- Canis limitations
  - Background field impractical
  - Planar vs. conformal (3D) configuration
  - ~10 km HTS utilization
  - Edge effects

Criteria	**Canis Magnet**	**Preliminary Eos Shaping Coil, Typical**
Operating current	150 A	295 A
Operating temperature	20 K	20 K
Number of pancakes per coil	10	20
Total current per coil	225 kA-turn	1,180 kA-turn
Stored energy per coil	4.4 kJ	345 kJ
WP current density	180 A/mm^2	~200 A/mm^2
Coil shape	Rounded rectangle	Circular
Winding (major) diameter	190 mm	480 mm
Field in bore, self-field	1.8 T	3.5 T
Peak self-field on HTS	3.7 T	7.2 T
Peak background field ⊥ to HTS	~0 T	9.3 T
Peak total field on HTS	3.7 T	14.7 T
Fraction of critical, total field, 20 K	~28%	80%
Coil architecture	Soldered metal insulation (SMI)	Partially insulated (PI)

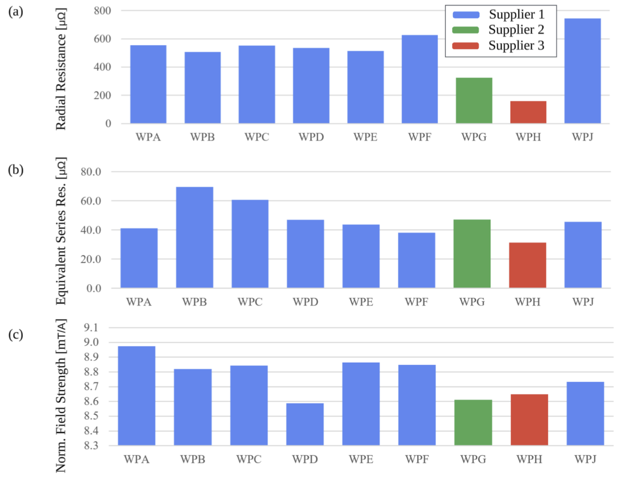
Shaping Coil Manufacturing



- 50+ DPs manufactured and acceptance tested in liquid nitrogen (LN2)
- 10 WPs assembled and acceptance tested in LN2
- 10 WPs characterized at 20 K
- Characterized for:
  (a) equivalent series resistance (ESR), (b) radial resistance, and (c) field strength



DP, 77 K



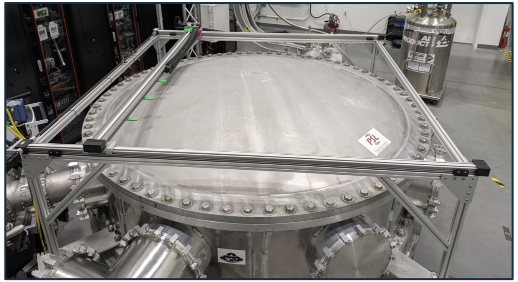
WP, 77 K

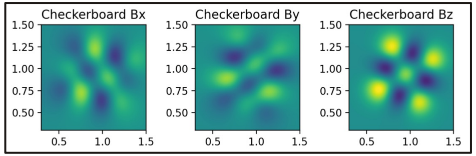
WP, 20 K

Field Shaping Campaign

- Field shapes should be Eos-meaningful
  - Take “patches” from Eos last closed-flux surface boundary
  - Concave and convex, high and low curvature
  - Use shapes from toroidal angle $\varphi = 0$ plasma section
  - Match Canis $\mathbf{B} \cdot \hat{z}$ iso-surface shape to Eos $\mathbf{B} \cdot \hat{n} = 0$ contours at 9 discrete “anchor points”

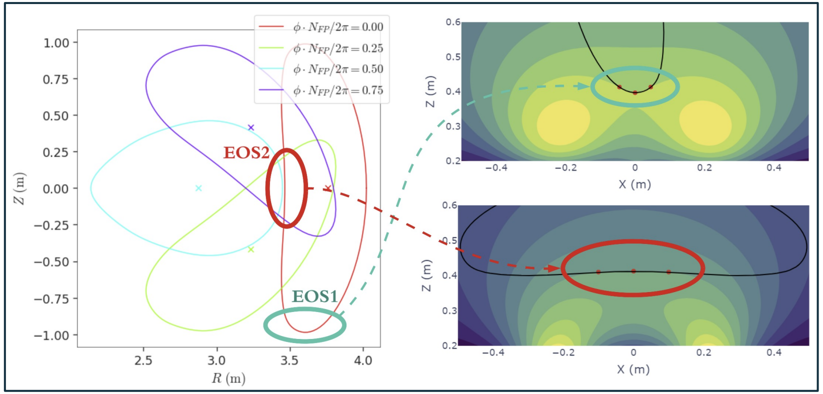
- Measure field shapes with ATLAS scanner
  - 2D gantry system with ±0.1% Hall effect sensor
  - Calibrate orientation with “checkerboard” field pattern

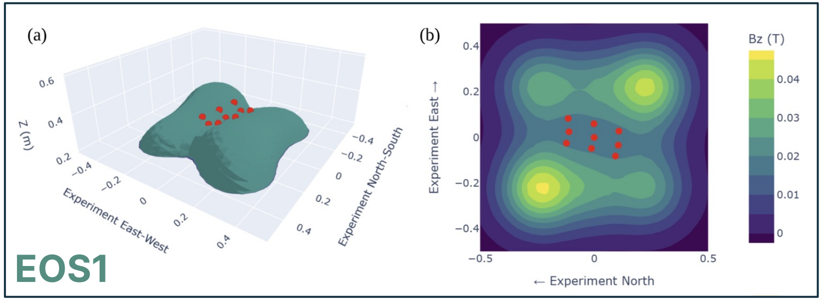


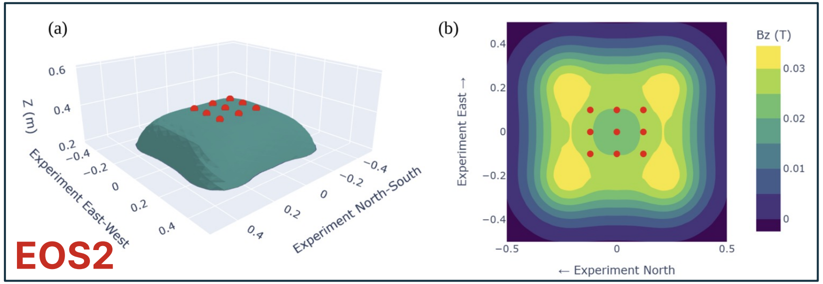


Group	Degree of Freedom		
	X	Y	Z
Scan Plane Offset [m]	-0.9508	-0.9362	0.2418
Scan Plane Rotation [°]	-0.0262	0.0254	72.70
Hall Probe Rotation [°]	-0.484	-0.808	0.330

(a) Canis iso-surface showing 9 anchor points in 3D space
(b) Field projection on ATLAS scanning plane, 25 cm from array midplane





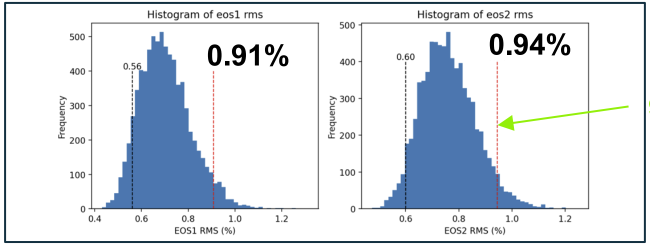


Field Error

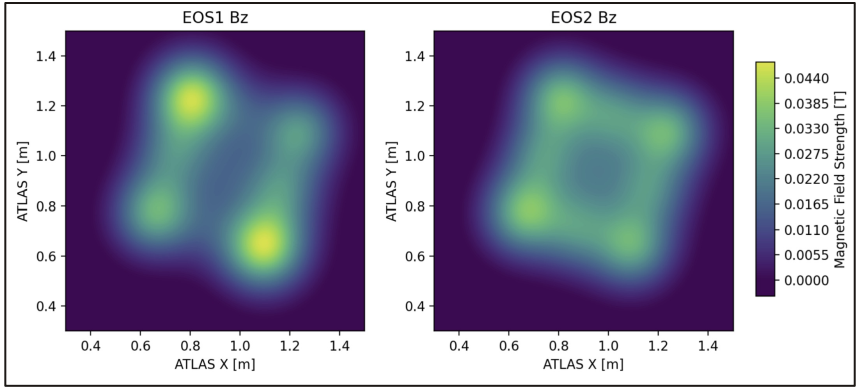
- Generate 3D **B** prediction from as-built WP kernels
- Project **B** prediction onto calibrated ATLAS plane
- ATLAS scan at 12.5mm resolution
- Calculate error between prediction and scan

Error	Field Shape	
	EOS1	EOS2
E_{RMS} [%] (mT)	0.56% (0.27 mT)	0.60% (0.24 mT)
Peak $\|\mathbf{B}\|$ Error [%] (mT)	1.38% (0.66 mT)	1.18% (0.48 mT)
Peak B_z Error [%] (mT)	1.33% (0.62 mT)	1.17% (0.45 mT)

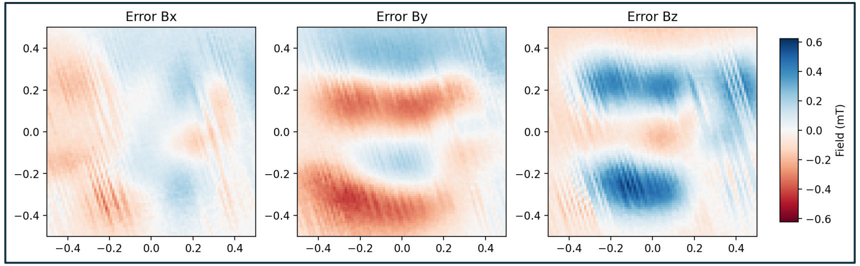
- Bound error with Monte-Carlo analysis
  - Hall sensor total uncertainty: ±0.9% (includes pos.)
  - Magnet X||Y position, cold: ±0.5 mm
  - Find new best fit ATLAS plane and calculate E_{RMS}



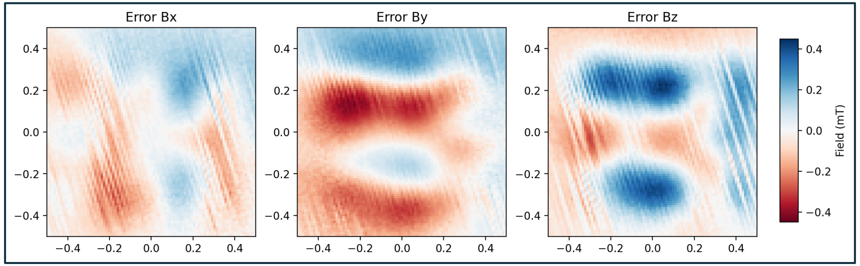
95th percentile



EOS1

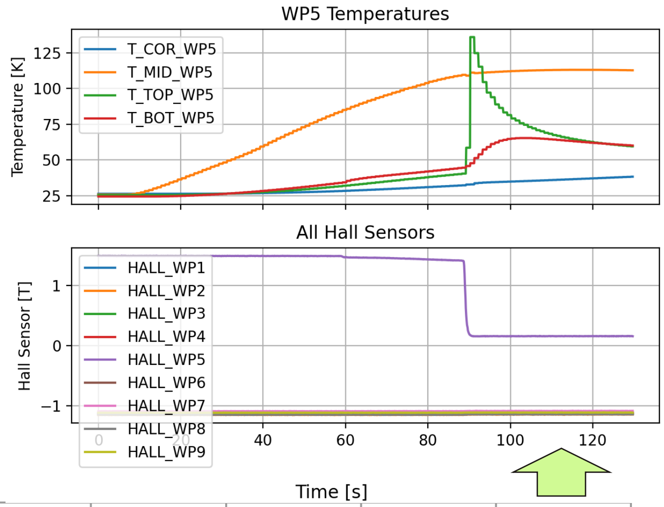


EOS2

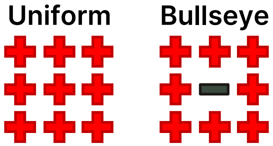


Array Quench

Scenario 4:
Bullseye Quench in WP5
Energy



- Goals
  - Induce quench with 300 W heaters at coil midplane
  - Demonstrate self-protection
  - Demonstrate non-propagation of quench
  - Evaluate quench time scale
  - Evaluate minimum quench energy (heater duration)
- Quench Experiments
  1. Uniform at ~I_{OP}, quench center coil
  2. Uniform at ~I_{OP}, quench edge coil
  3. Uniform at ~I_{OP}, quench corner coil
  4. "Bullseye", quench center coil (negatively charged)



- Results
  - **All survived with no measured performance change**
  - **No quenches propagated to neighboring coil**

Experiment	1	2	3	4
Quenching coil	WP5/A **Center**	WP2/B **Edge**	WP3/G **Corner**	WP5/A **Center**
Pattern	Uniform	Uniform	Uniform	"Bullseye"
Quenching coil R_{RAD}, 20 K	~335 µΩ	~321 µΩ	~138 µΩ	~335 µΩ
Minimum quench energy	~21 kJ	~27 kJ	~42 kJ	~21 kJ
Incubation period	~86 s	~170 s	~239 s	~81 s
Quench duration	~1.5 s	~1.5 s	~2.0 s	~1.5 s
Measurable performance change post-quench?	**No**	**No**	**No**	**No**
Quench propagates to other coils?	**No**	**No**	**No**	**No**

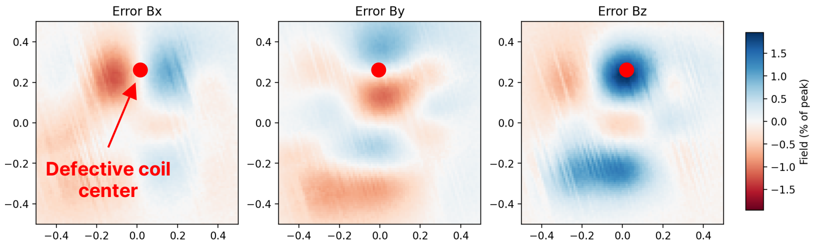
Defect Tolerance

- Short out a full DP in an edge coil
  - Closed-loop field control overdrives short coil
  - **E_{RMS} increases by ≤0.17%**
- Install center coil at ~2.8° tilt
  - Detect and quantify tilt algorithmically

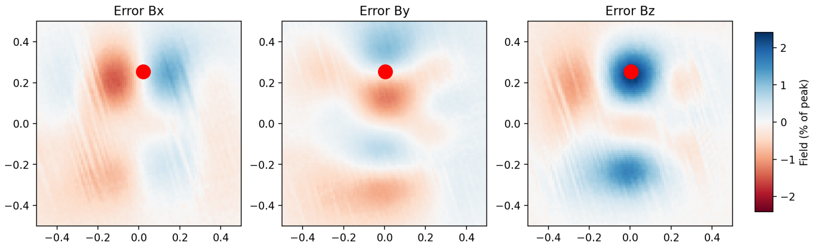
Hall Data → ML Find Bad Coil → Optimization -or- ML → Tilt Estim. → Update Field Targets

  - **Decrease RMS field error at anchor points 0.73% → 0.14%**

EOS1
Shorted DP field error

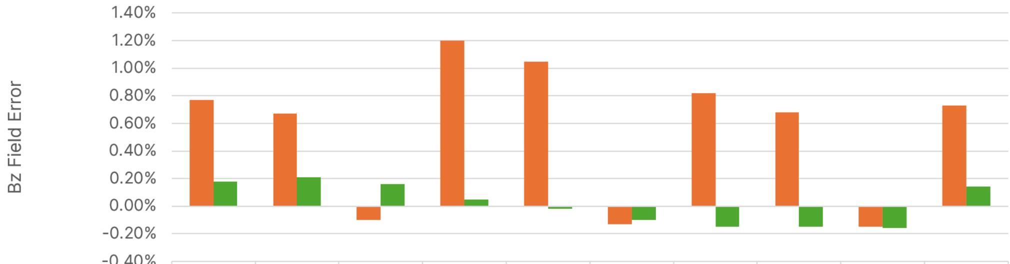


EOS2
Shorted DP field error



"Tilted" Winding Pack assembly

Uncorrected and Corrected Field Error at EOS1 Iso-Surface Anchor Points



	Anchor 1	Anchor 2	Anchor 3	Anchor 4	Anchor 5	Anchor 6	Anchor 7	Anchor 8	Anchor 9	RMS
Uncorrected Error	0.77%	0.67%	-0.10%	1.20%	1.05%	-0.13%	0.82%	0.68%	-0.15%	0.73%
Corrected Error	0.18%	0.21%	0.16%	0.05%	-0.02%	-0.10%	-0.15%	-0.15%	-0.16%	0.14%

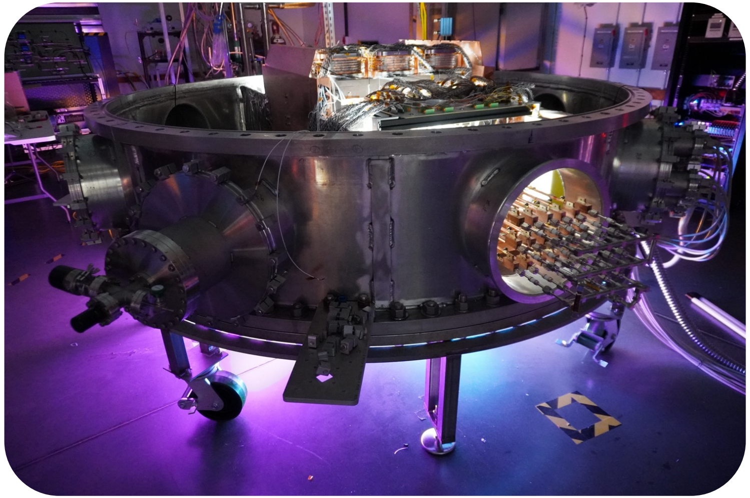
Conclusion

- Thea Energy prototyped a 3x3 array of planar shaping magnets

- The Canis magnet array program demonstrated:
  - Manufacturing rate up to 2 DPs/day
  - Closed loop control of magnetic field iso-surfaces
  - <1% RMS error for stellarator-relevant field shapes
  - Non-damage and non-propagation from quench
  - Tolerance to manufacturing and assembly defects

- Future shaping coil work
  - Further AI/ML defect detection and control development
  - Eos-scale shaping coil magnet
  - Eos “Field Shaping Unit” prototype

- Thank you!



Canis magnet array and cryostat

Stay in the loop

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