Fabrication status and test plans for a 5 T, NbTi CCT magnet producing combined function fields in an elliptic aperture

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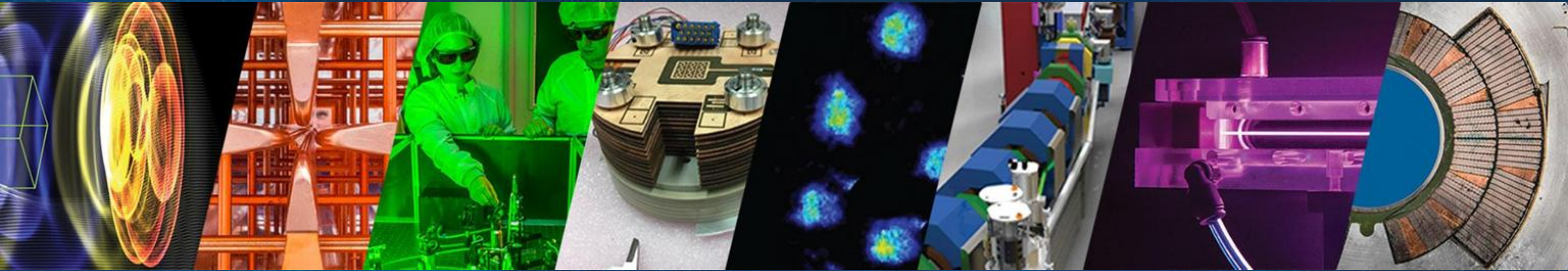


US-MDP General Meeting

February 11th, 2026

BERKELEY LAB

ACCELERATOR TECHNOLOGY & APPLIED PHYSICS DIVISION ATAP

U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

- Motivation for elliptic bore, combined function SC magnets
- Application to the CCT winding geometry
- Design and fabrication of a ~5 T demonstrator magnet

This work is funded outside of MDP, but highly relevant to Area IV: Exploratory studies

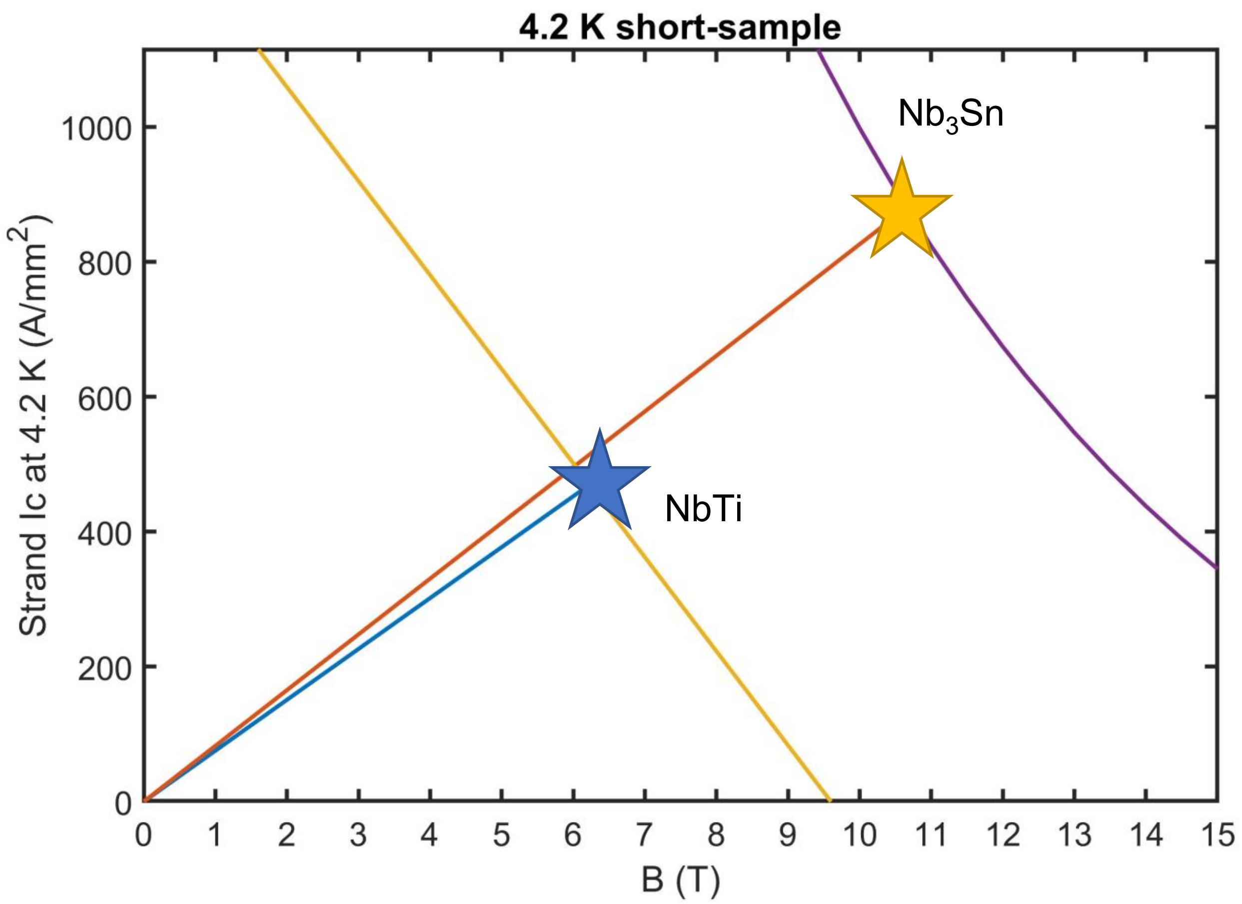
Higher T / All-HTS Sustainability	IR & Combined function magnets	Interfacing with Collider Studies
Area IV: Exploratory studies		

Sub-Area IV.b: Interaction Region and Combined Function Magnets

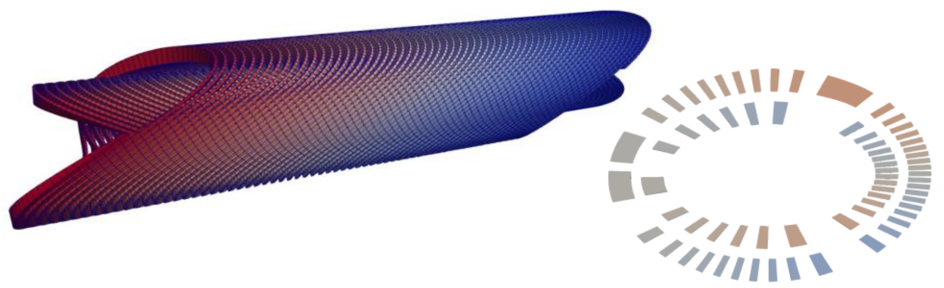
While future collider magnet technology typically focuses on ring dipoles due to their significant impact on overall facility cost and performance, additional accelerator magnets also play a crucial role in driving collider performance. Notably, the strong quadrupoles in the detector interaction region are essential for maximizing collider luminosity. Advances in accelerator magnet technology must address the unique challenges posed by these magnets.

Furthermore, innovative designs, such as combined-function magnets that enable unique lattice configurations, could introduce new collider design paradigms, ultimately enhancing overall physics capabilities.

High level program goal: demonstrate combined function fields in an elliptic aperture using CCT magnet technology



combined function CCT: 40 x 90 mm aperture, 600 mm length



Magnet #1: NbTi (~6 T cond, 3.8 T + 27 T/m)

- establish elliptic magnet fabrication techniques
- demonstrate performance and field quality for dipole + quadrupole combined function
- ~2.5 years from start (FY26)

Nb_3Sn (~11 cond)

- work out Nb_3Sn compatibility
- demonstrate high field

Follows past LBNL development sequence for circular bore CCT dipole magnets (https://doi.org/10.1109/TASC.2022.3155505)

Why combined function? Interest for future accelerators (e.g. muon collider) and fixed-field accelerators

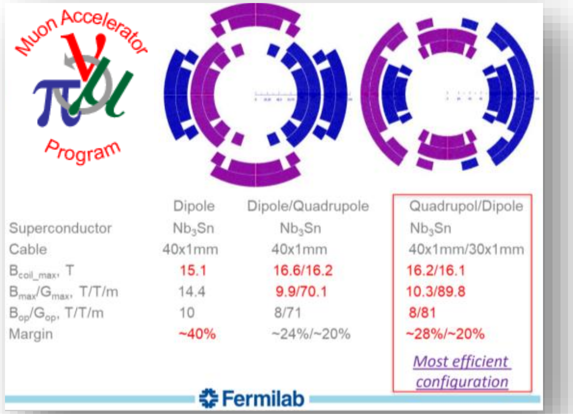
D. Novelli: muon collider ring magnet targets

Arc:

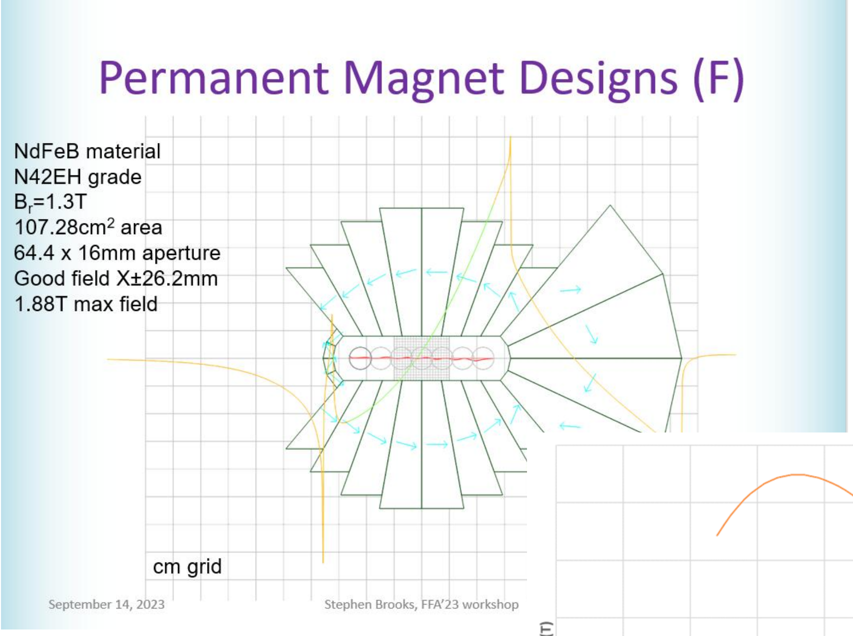
- Combined function magnets: B1, **B1+B2** and **B1+B3**
- B ≈ 8...16 T; G ≈ 320 T/m; G' ≈ 7100 T/m²
- Aperture ≈ 160 mm

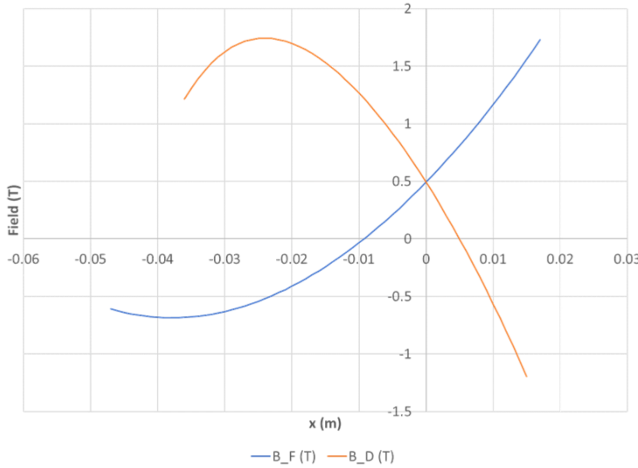
Final focus:

- Combined function magnets: B1, B2, **B1+B2**, **B1+B3**
- B ≈ 4...16 T; G ≈ 100...300 T/m; G' ≈ 12000 T/m²
- Aperture ≈ 120...300 mm



	Dipole	Dipole/Quadrupole	Quadrupol/Dipole
Superconductor	Nb_3Sn	Nb_3Sn	Nb_3Sn
Cable	40x1mm	40x1mm	40x1mm/30x1mm
B_{coil_max}, T	15.1	16.6/16.2	16.2/16.1
B_{max}/G_{max}, T/T/m	14.4	9.9/70.1	10.3/89.8
B_{op}/G_{op}, T/T/m	10	8/71	8/81
Margin	~40%	~24%/~20%	~28%/~20%
			Most efficient configuration



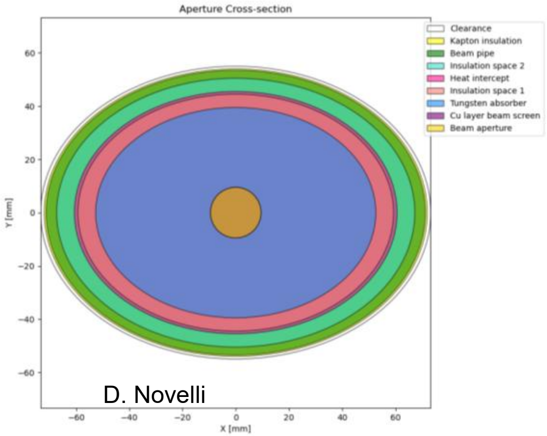


Scott Brooks, Permanent Magnet and Electromagnet Designs for Nonlinear FFA Fields, FFA23

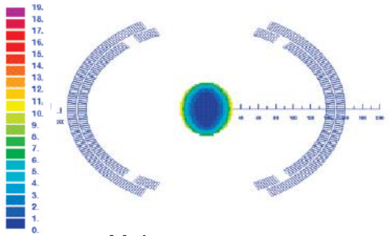
Why non-circular (elliptic) aperture? It is a better fit for concentrating radiation shielding at the midplane and non-circular sampling of the magnet aperture by the beam

Circular beam aperture, but radiation shielding concentrated at midplane creates an elliptic shape

MuCol



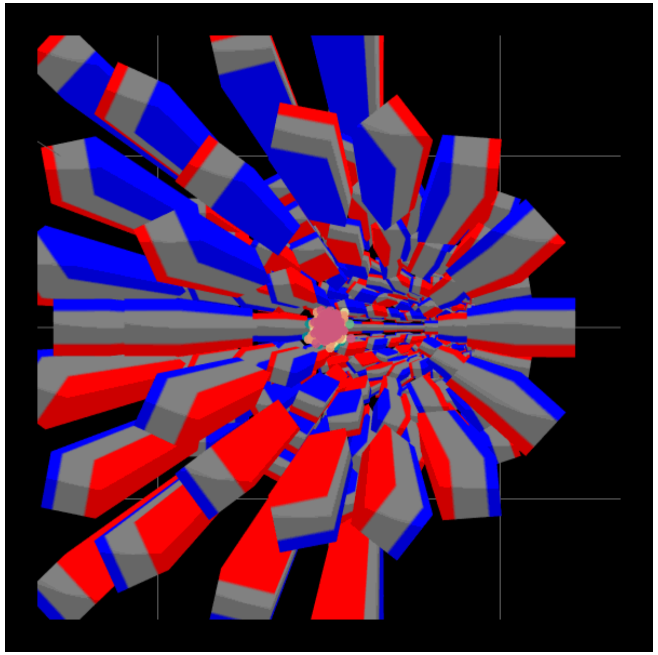
Muon Accelerator Program



M. Lopes

https://accelconf.web.cern.ch/ipac2012/papers/thppd037.pdf

Beam(s) sampling a non-circular region (common for fixed-field-accelerators)



From: Adam Steinberg, Design of a Closed-Dispersion Arc with a Large Energy Acceptance for the TURBO Project, FFA23

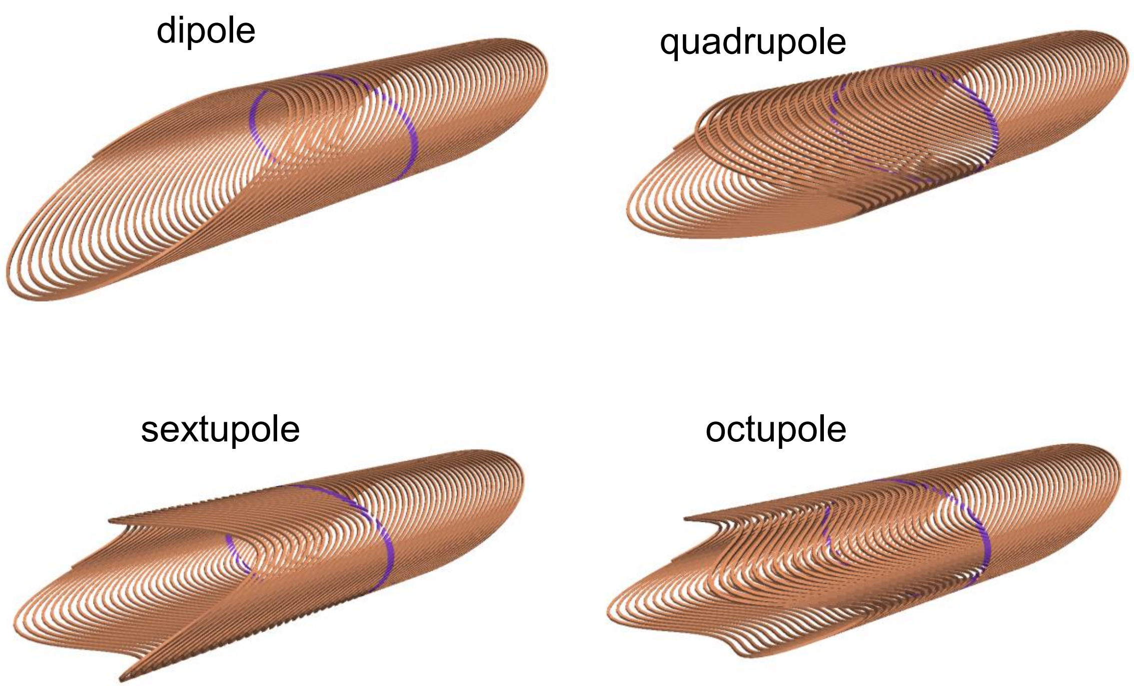
Why CCT? The winding path for producing circular harmonics in an elliptic aperture can be analytically derived from the elliptic current density

The CCT path has a 3D periodic axial symmetry, the current density averaged over this period can be related to the desired current density to derive the winding parameters

$$\boldsymbol{p}(\psi) = a \cosh \eta_0 \cos \psi \hat{\boldsymbol{x}} + a \sinh \eta_0 \sin \psi \hat{\boldsymbol{y}} + p_z(\psi)\hat{\boldsymbol{z}},$$

Desired	CCT axial path $p_z(\psi)$	B_n (e.g., $\mathrm{T/m}^{n-1}$)
B_1	$\frac{a \sinh \eta_0}{\tan \alpha} \sin \psi$	$-\frac{\mu_0 I_0 \sinh \eta_0}{w \tan \alpha e^{\eta_0}}$
B_2	$\frac{a \sinh \eta_0}{2 \tan \alpha} \sin 2\psi$	$-\frac{2\mu_0 I_0 \sinh \eta_0}{aw \tan \alpha e^{2\eta_0}}$
B_3	$\frac{a \sinh \eta_0}{\tan \alpha} \left(\frac{1}{e^{2\eta_0}} \sin \psi + \frac{\sin 3\psi}{3} \right)$	$-\frac{4\mu_0 I_0 \sinh \eta_0}{a^2 w \tan \alpha e^{3\eta_0}}$
B_4	$\frac{a \sinh \eta_0}{\tan \alpha} \left(\frac{2}{e^{2\eta_0}} \frac{\sin 2\psi}{2} + \frac{\sin 4\psi}{4} \right)$	$-\frac{8\mu_0 I_0 \sinh \eta_0}{a^3 w \tan \alpha e^{4\eta_0}}$

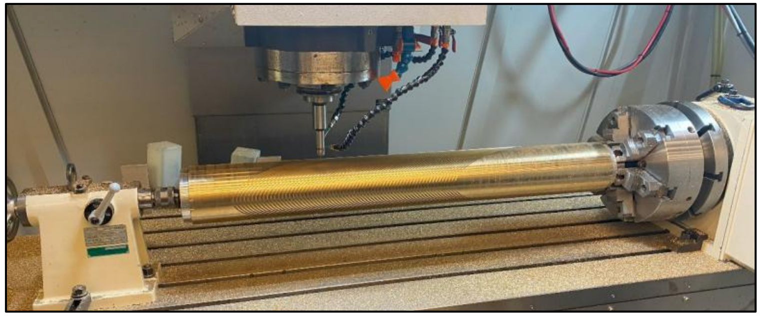
Axial modulation of the winding path controls the harmonic content (similar to circular CCT) allowing for single or combined function coils



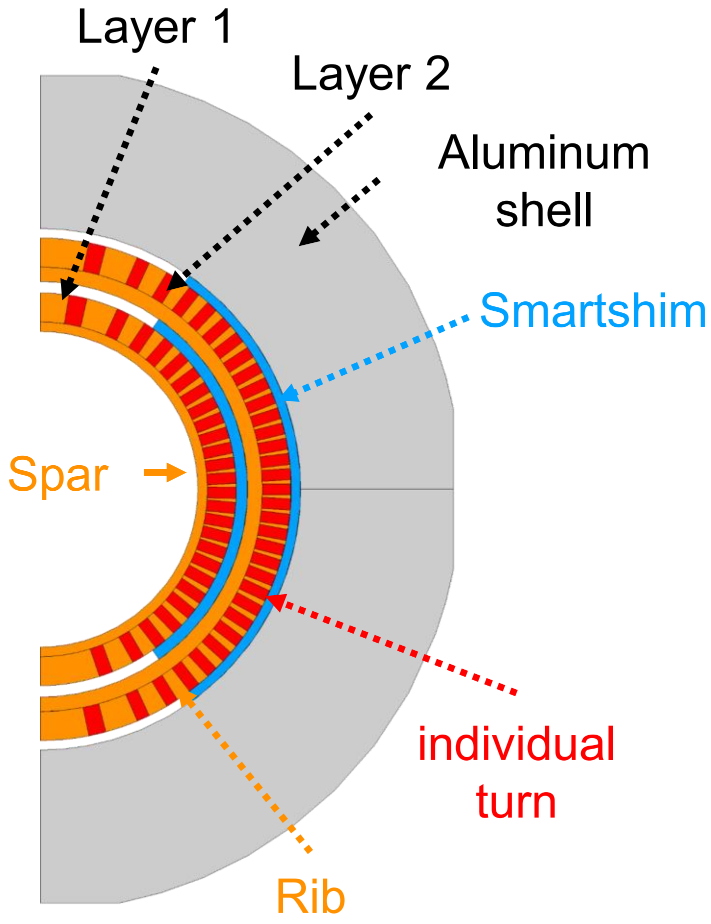
More details in our recent paper: 10.1103/PhysRevAccelBeams.27.022402

Why CCT? The CCT magnet fabrication process at LBNL does not require significant changes for an elliptic aperture (modular by layer, winding mandrel is main tooling)

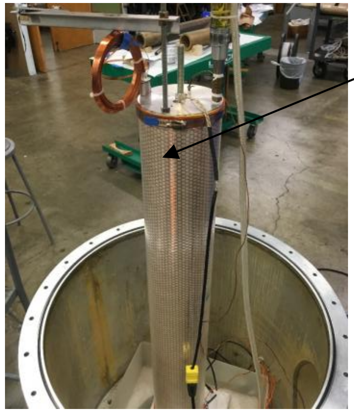
The main challenge is to fabricate winding mandrels with elliptic aperture -> we will show our progress on this



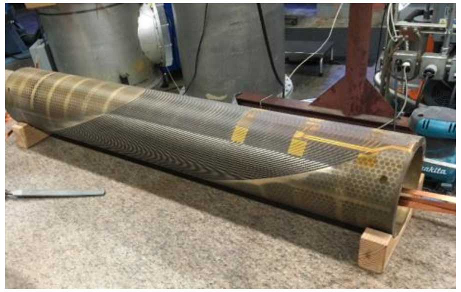
Magnet assembly / disassembly with inflatable epoxy shims



Individual layers are wound, reacted, and impregnated separately (epoxy, wax, filled wax)



Flow media + shrink wrap for potting



D. Arbelaez, J.L. Rudieros Fernandez

Goals and constraints for the design of the NbTi prototype

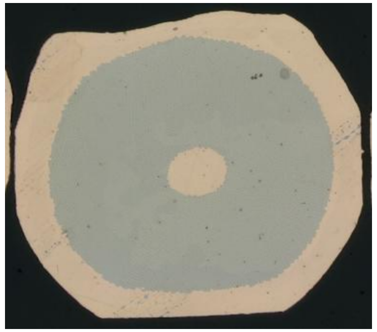
High level magnet design goals

- 40 x 90 mm elliptic aperture following 1-5 GeV/c muon FFA study
- combined function fields (dipole + quadrupole)
- ~5-6 T field level compatible with existing NbTi cable
- short as possible that allows for magnetic field measurements of straight-section

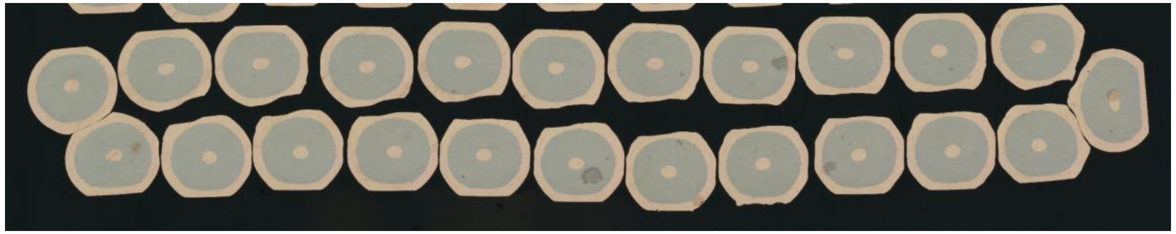
Conductor constraint: use available NbTi strand / cable

0.805 mm strand
from SSC

1:3:1.0 Cu:SC
Jc = 1635 A/mm^2
at 7 T, 4.2 K



23 strand Rutherford cable (1.44 x 10 mm)

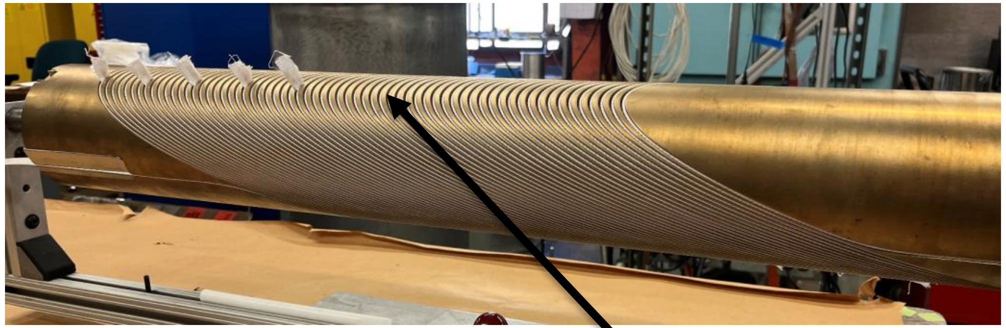


Images from Jean-Francois Croteau

The windability of elliptic and combined function CCT's are different, and we are learning the limits through winding tests

Normal CCT dipole

The challenging region to wind is limited to the poles



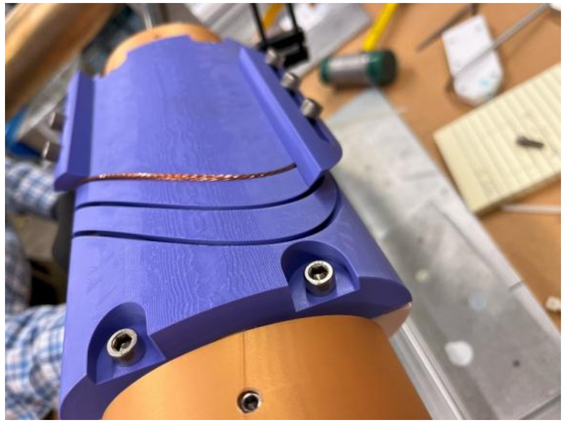
Direct tradeoff between field efficiently and windabilty through means of the winding tilt angle

Elliptic CCT combined function

Challenge at the poles + potential for other challenging regions

Crossing angle over major axis has strong influence on hardway bending

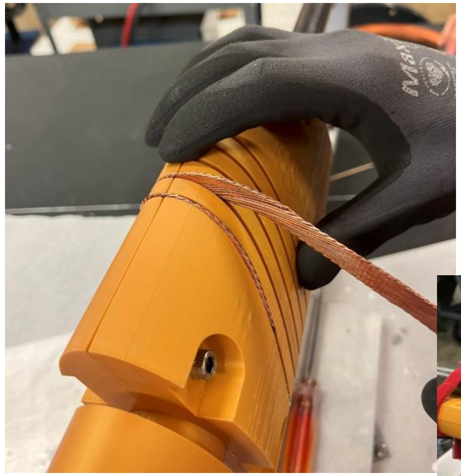
Radial confinement of cable can be tricky, even in "easy" regions



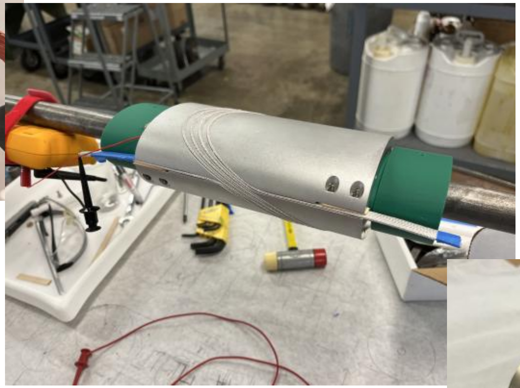
Yufan Yan + Brian Palmer

Our final coil design for the prototype resulted from combined magnetic optimization and coil winding tests

3D printed plastic



CNC Aluminum

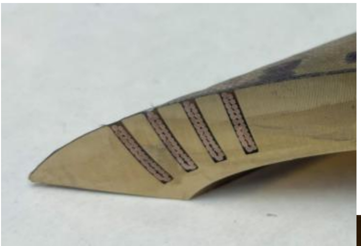


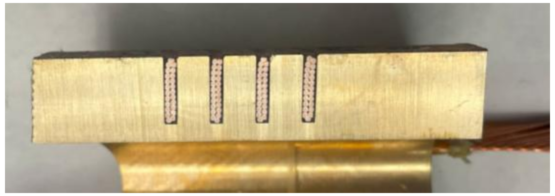
CNC Aluminum bronze (final geo.)

Our winding tests are also working out the fabrication process for aluminum bronze mandrels with elliptic aperture

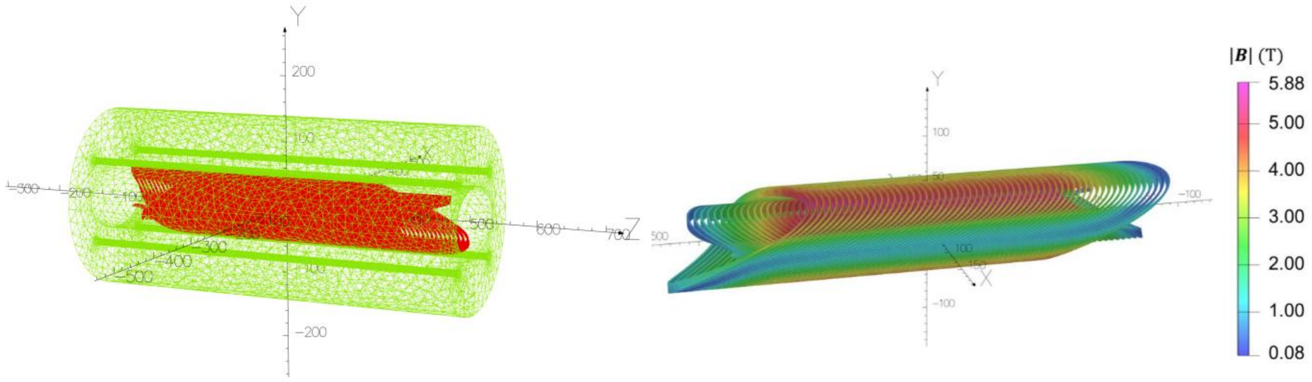
We potted and cut the final short coil

- developing the potting techniques for elliptic aperture
- validating the final conductor position

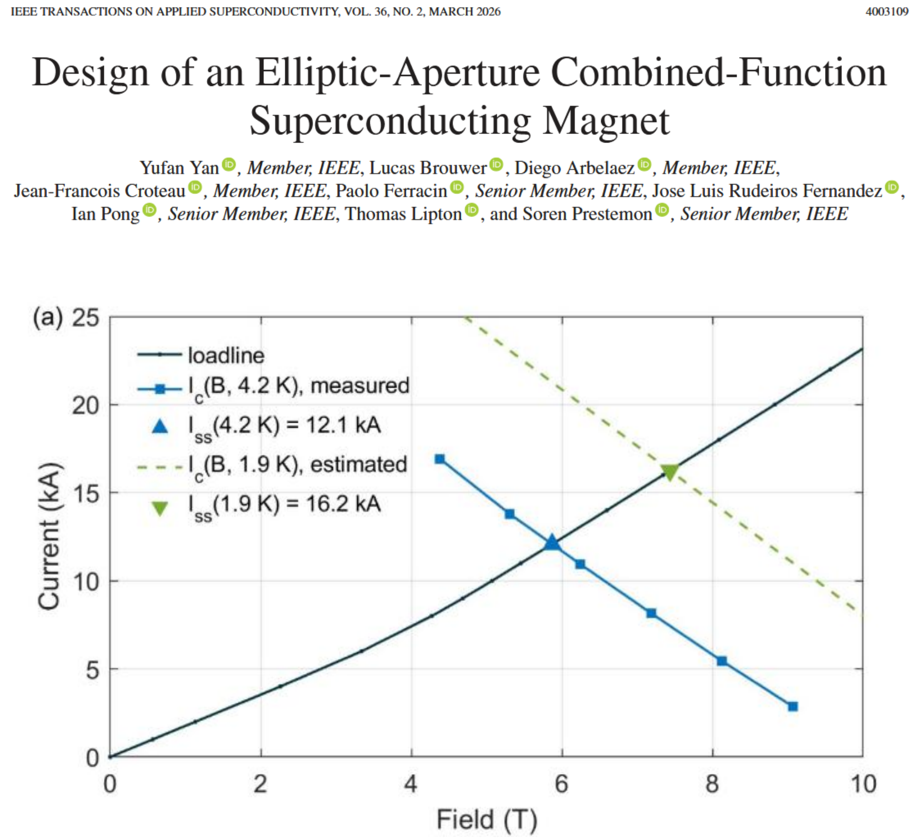




5 T Magnet Design Overview



clear bore	90 mm x 40 mm
dipole to quadrupole ratio	$rf = 1.8571$
number of layers	2
CCT tilt angle	22.5 °
number of turns	57
magnet physical length	600 mm
uniform field region for measurement along z-axis	$\lvert b_n(n \geq 3)\rvert < 1$ across length ~ 200 mm
peak field	~ 6 T field-on-conductor for NbTi ~ 11 T for Nb3Sn


IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 36, NO. 2, MARCH 2026 4003109

Design of an Elliptic-Aperture Combined-Function Superconducting Magnet

Yufan Yan, *Member, IEEE*, Lucas Brouwer, Diego Arbelaez, *Member, IEEE*, Jean-Francois Croteau, *Member, IEEE*, Paolo Ferracin, *Senior Member, IEEE*, Jose Luis Rudeiros Fernandez, Ian Pong, *Senior Member, IEEE*, Thomas Lipton, and Soren Prestemon, *Senior Member, IEEE*

NbTi @ 4.2 K	75 %	83 %	SS
current (kA)	9.0	10.0	12.0
dipole field (T)	-3.55	-3.83	-4.36
quadrupole (T/m)	-24.83	-26.97	-31.40
field-on-conductor (T)	4.68	5.07	5.85

https://doi.org/10.1109/TASC.2025.3645595

Circular harmonics at center vs. magnet current

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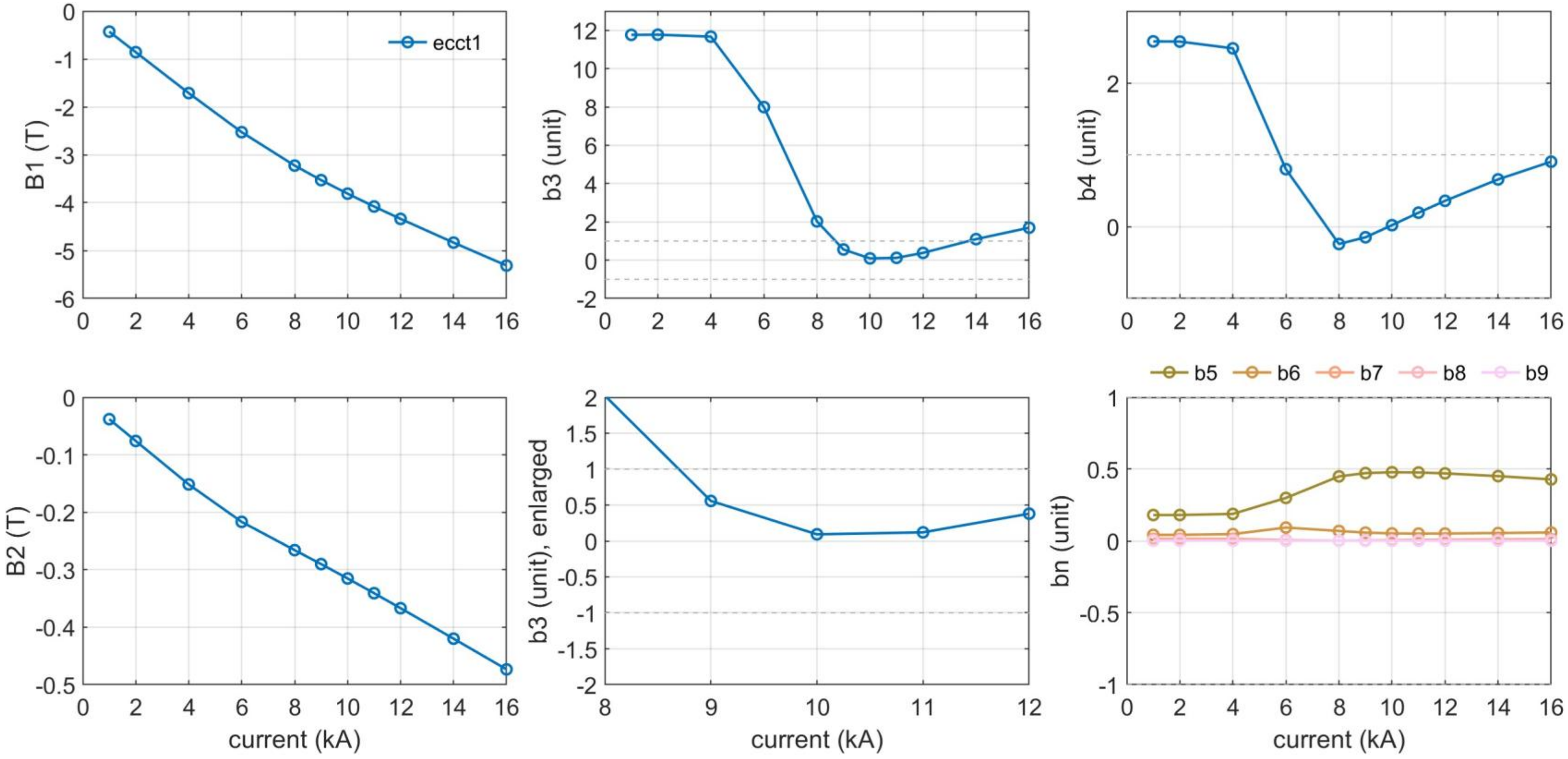
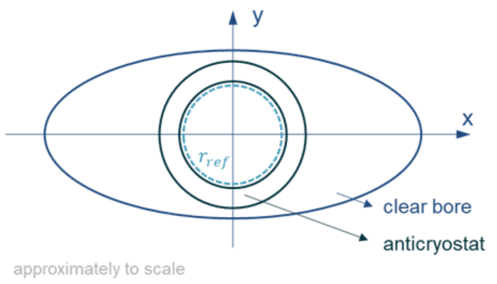
All higher order < 1 unit at nominal value of 10 kA





- 40 x 90 mm clear bore
- circular rref = 11.75 mm
- working with Joe DiMarco at FNAL on probe design

**b3 winding components added during coil design to componesate for saturation effects

Expected Field Profile: Harmonics along Z-Axis

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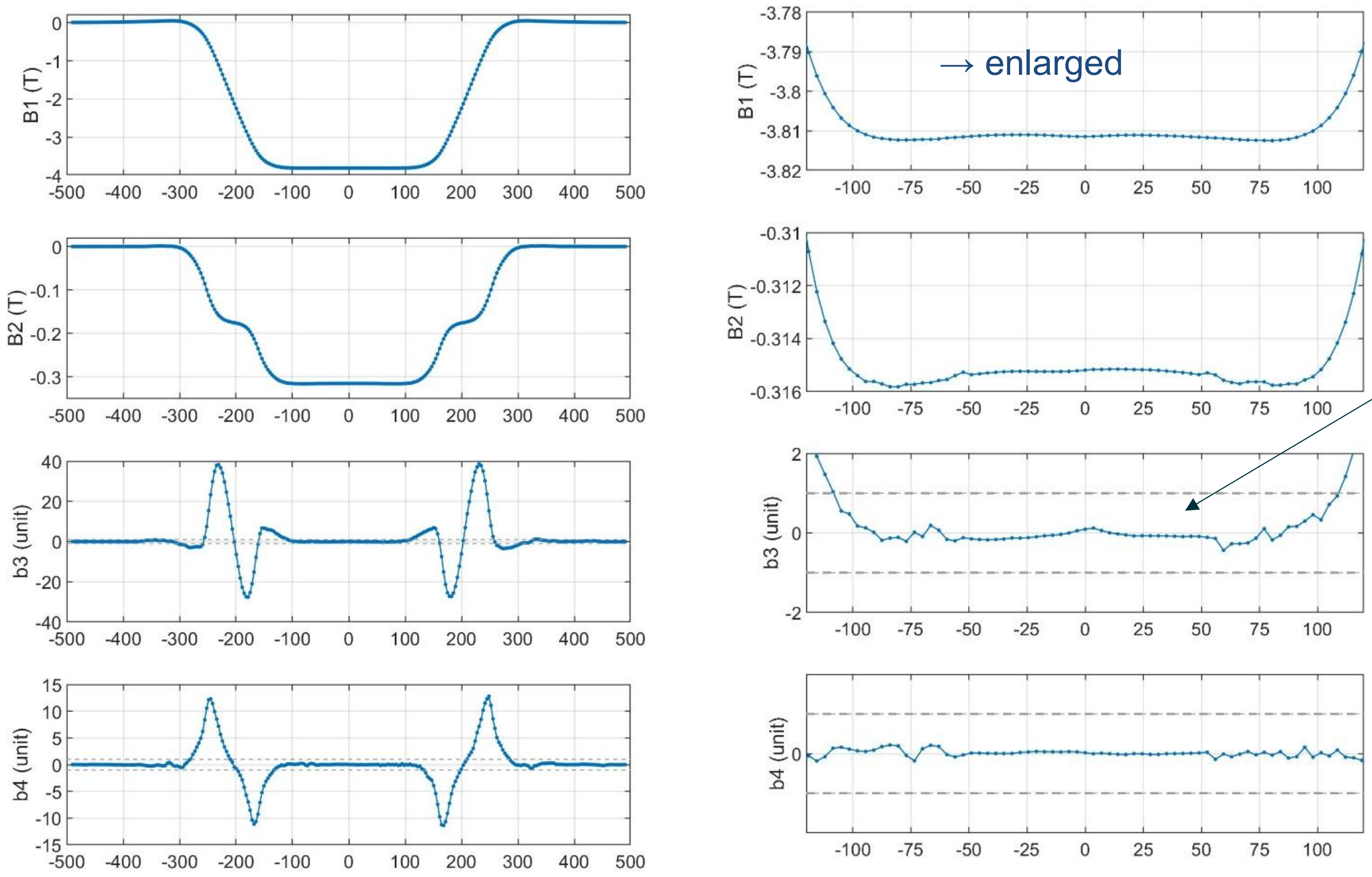
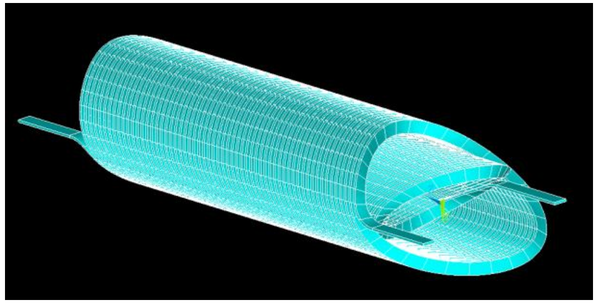
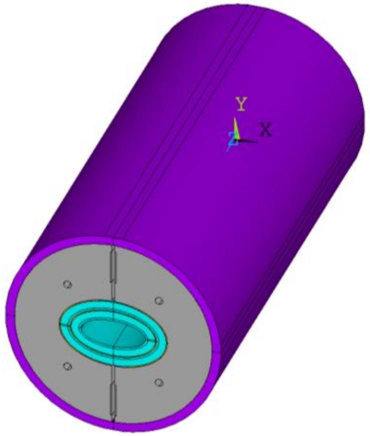


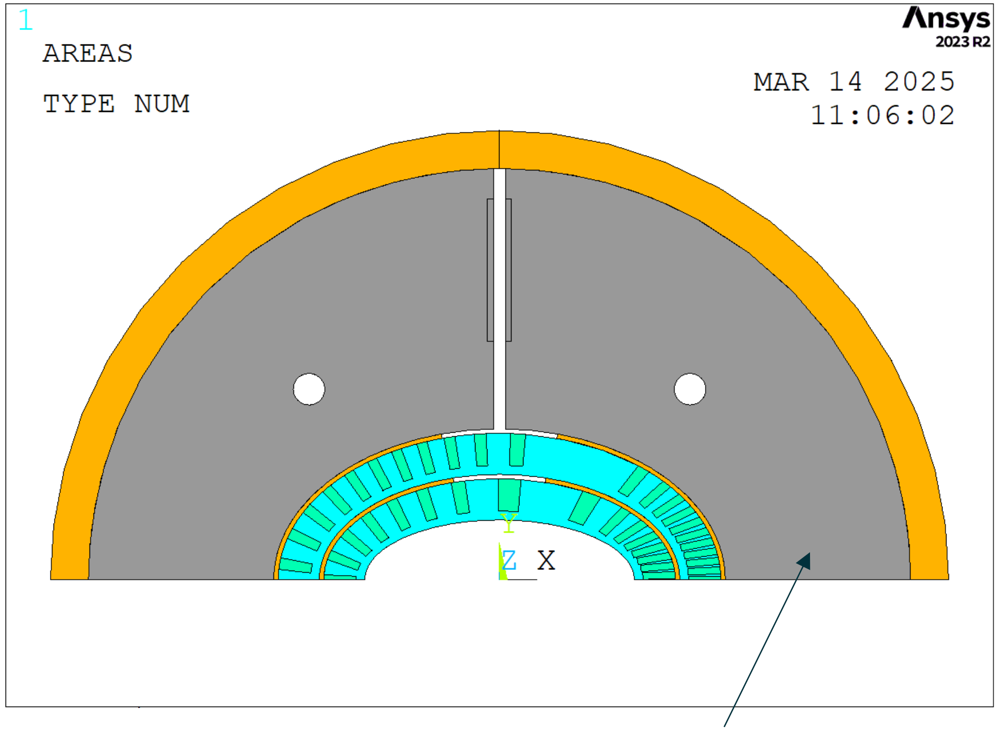
We have roughly 200 mm of straight-section based on b3 < 1 unit

2D/3D mechanics with simplified structure

- step1: prestress through the bladder (47.6 mm wide, 10 mm from the top)
- step2: smart shims added between coil and yoke, then release the pre-stress
- step3: cooldown
- step4: powering to 12.0 kA (4.2 K short-sample)



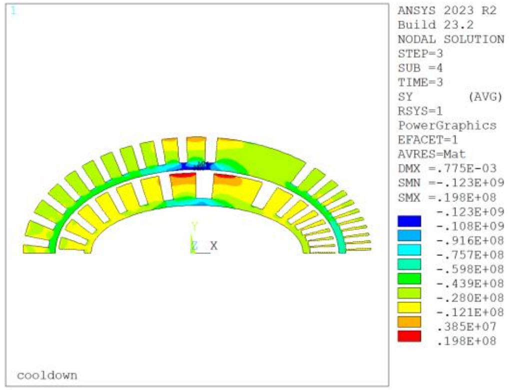


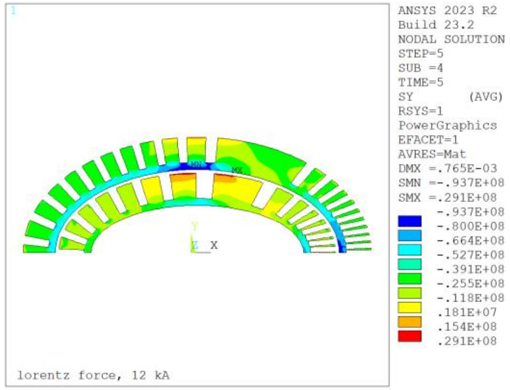


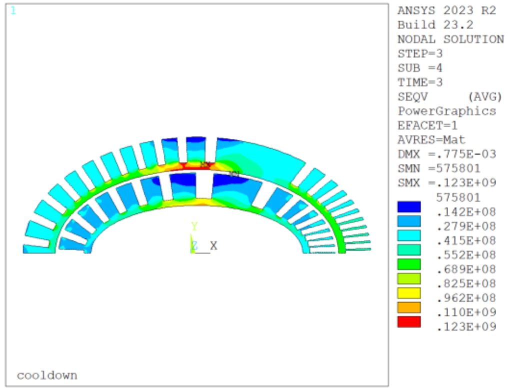
Iron blends from elliptic boundary to circular shell (for manufacrtoring)

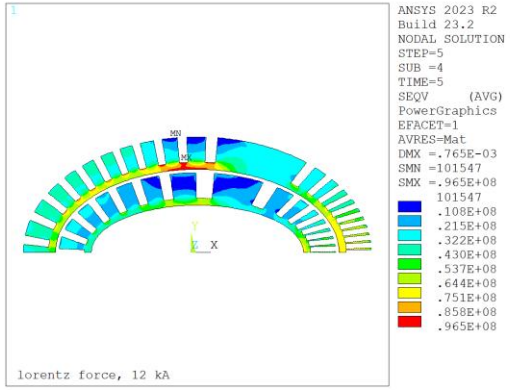
Mandrel stress is below criteria in 2D/3D

2D, cooldown, 12 kA



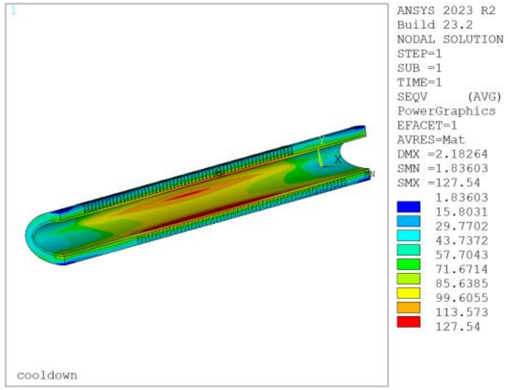


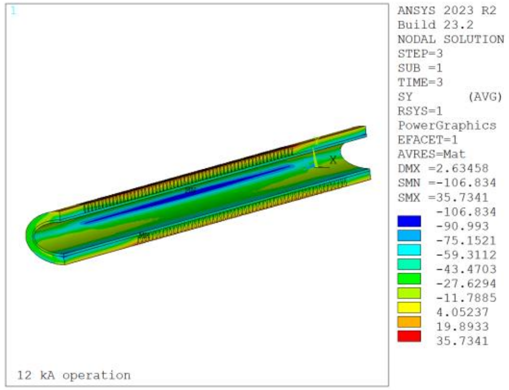


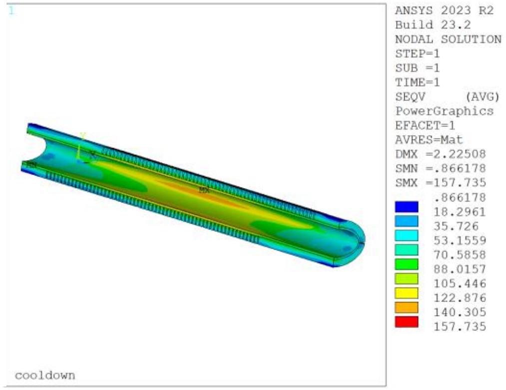


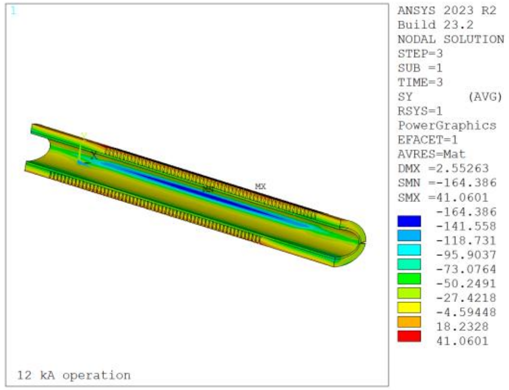
~125 Mpa max

3D, cooldown, 12 kA









~145 Mpa max

Structure stress is below criteria in 2D/3D

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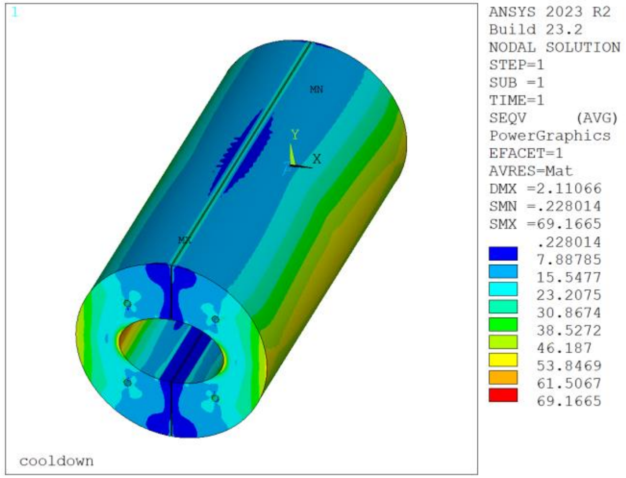
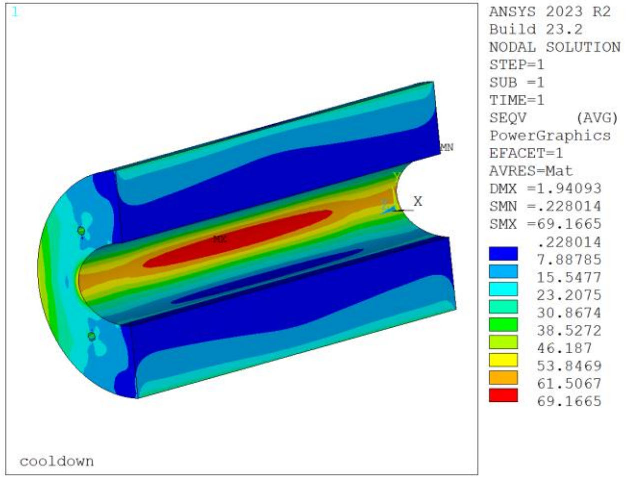
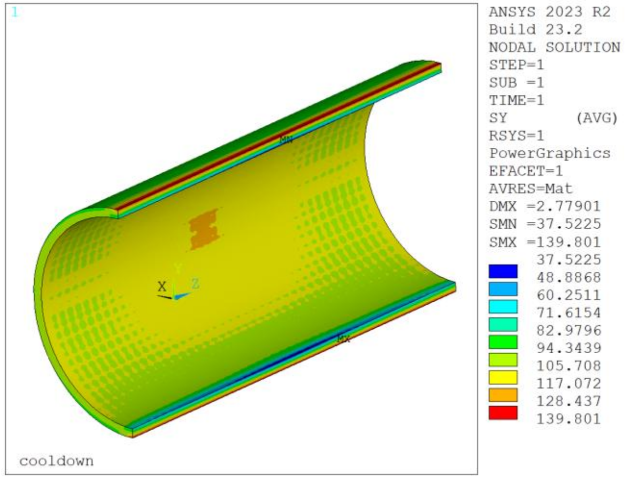
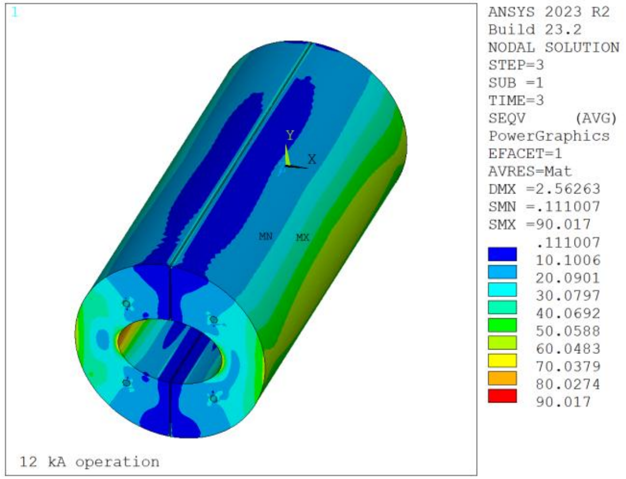
Yoke maximum is ~90 MPa

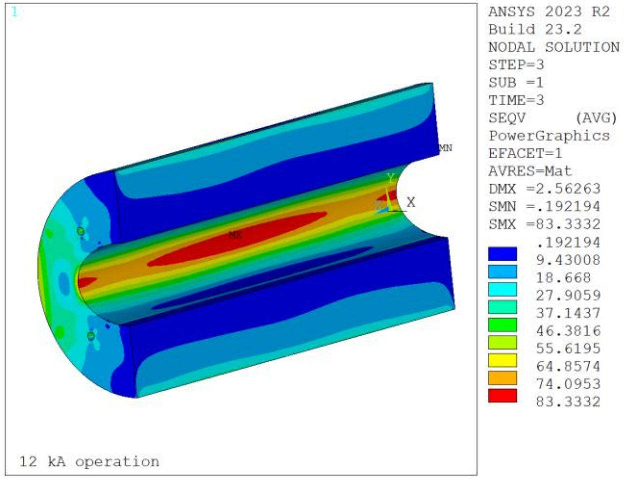


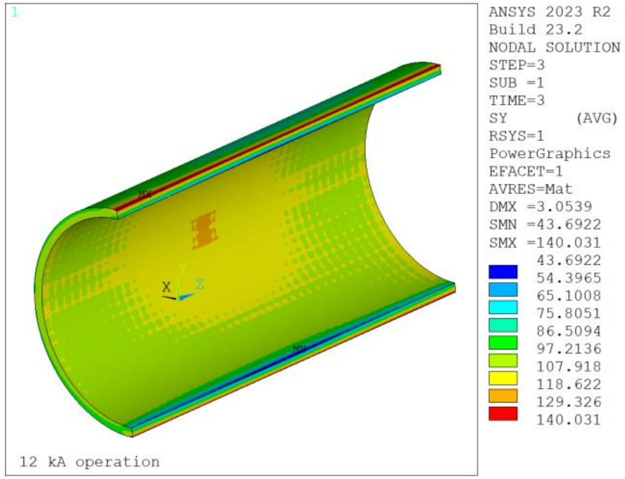


Shell maximum is ~140 MPa



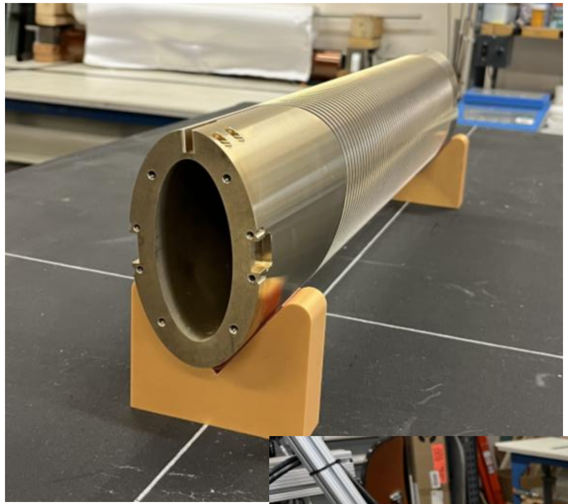






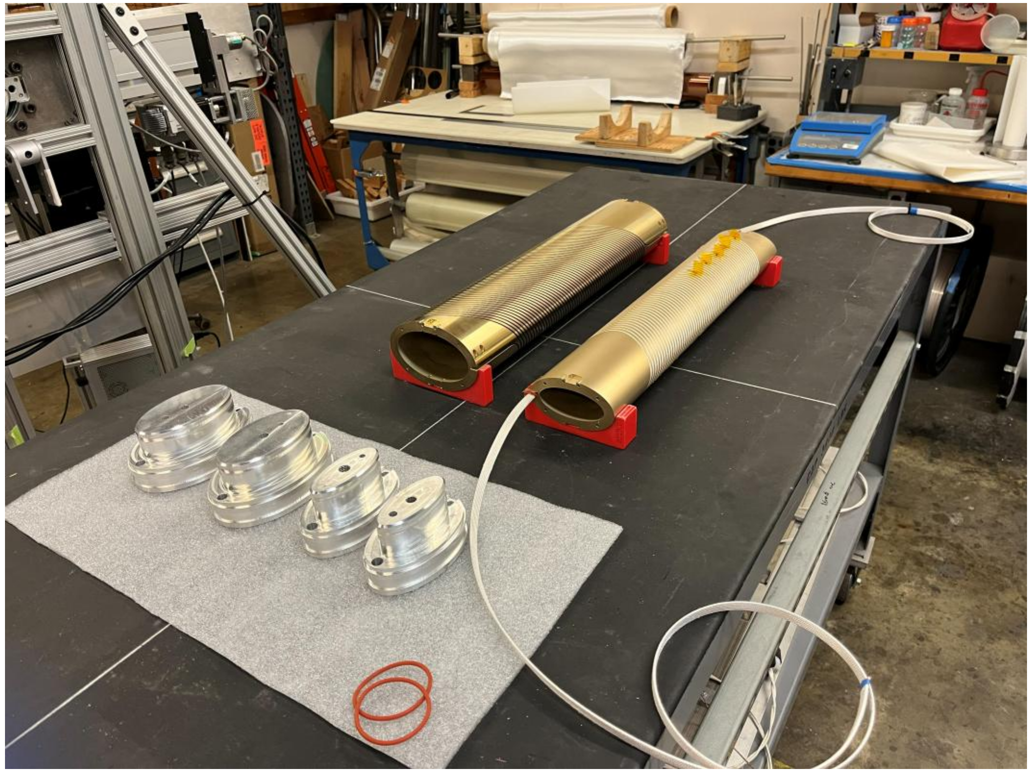
Mandrel fabrication

Wire EDM inner aperture out of round stock



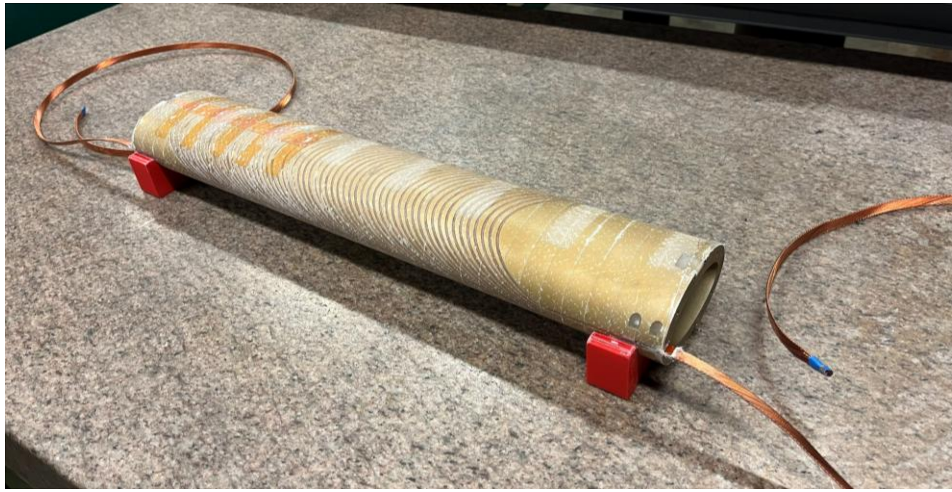
CNC of OD and
2.1 x 10.7 mm
grooves for cable

Coil winding

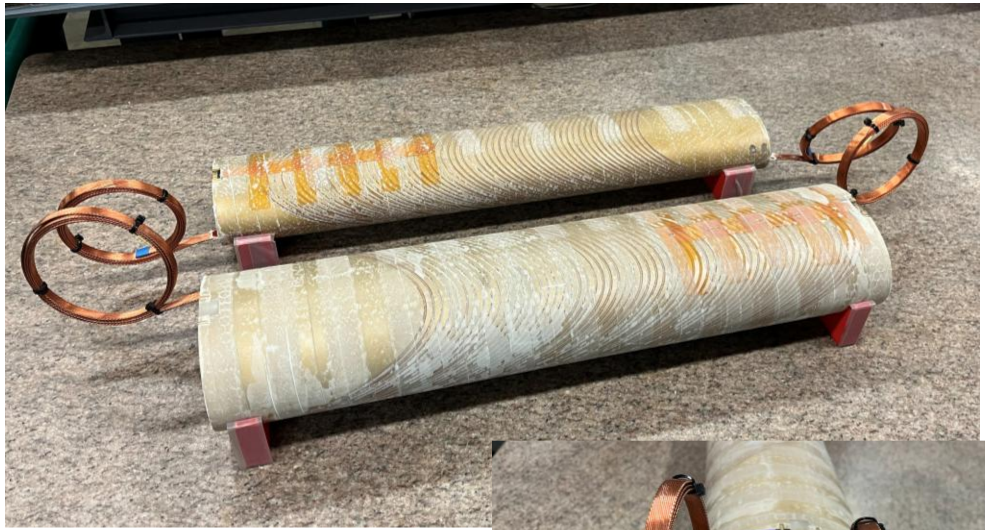


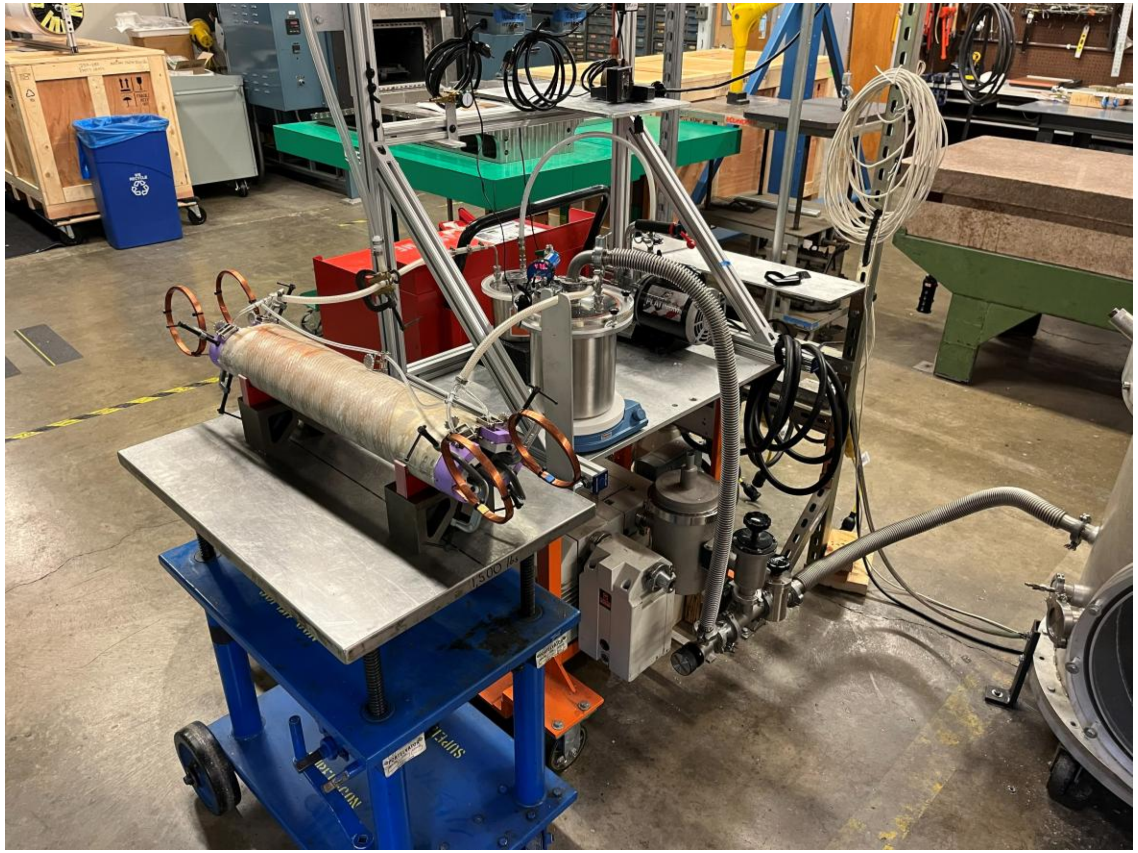
Paraffin wax vacuum impregnation with standard techniques for CCT

Vacuum bagging + VPI -> no special tooling for elliptic shape



Layer to layer assembly with epoxy-inflatable Kapton bags

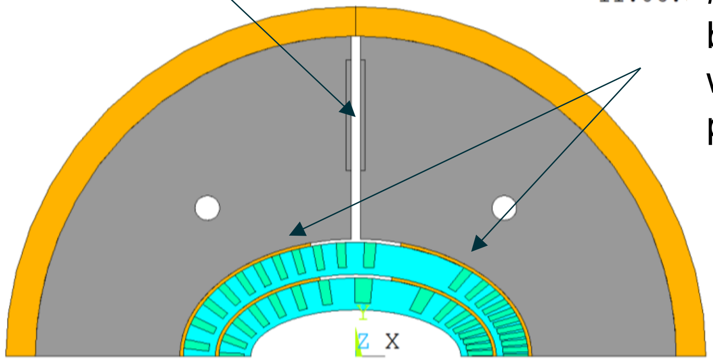




Coilpack to structure assembly is almost complete

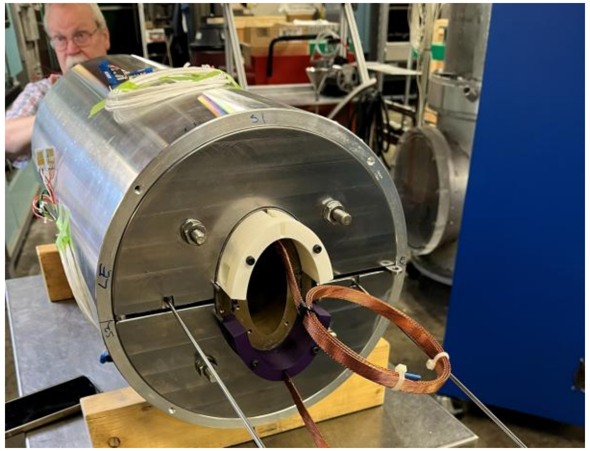
#1 Inflate stainless bladders with air to stretch shell (250 PSI)

#2 Inflate epoxy-filled Kapton bags between coils and yoke while bladders still under pressure



#3 Release bladder pressure when shims are cured (~2 weeks)

Presently, shims are mostly cured, and we are waiting to release pressure next week

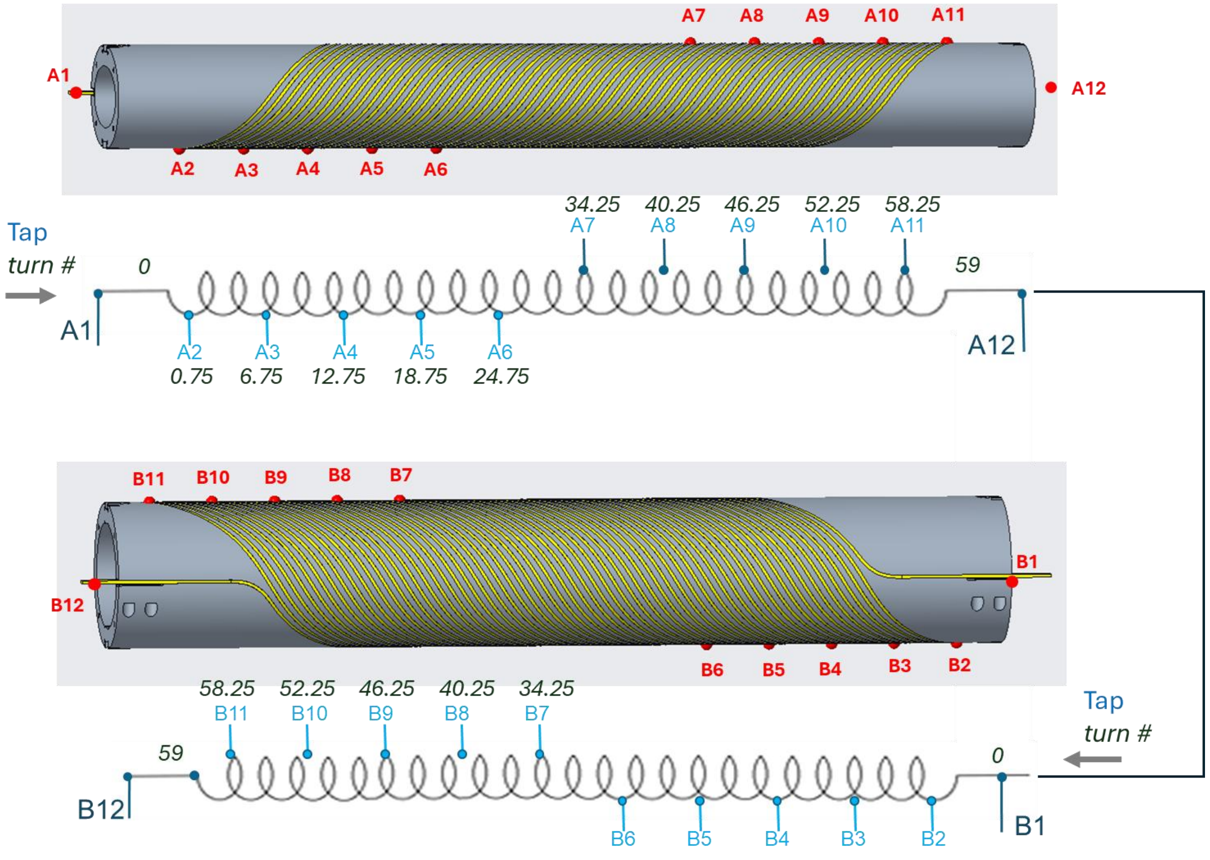


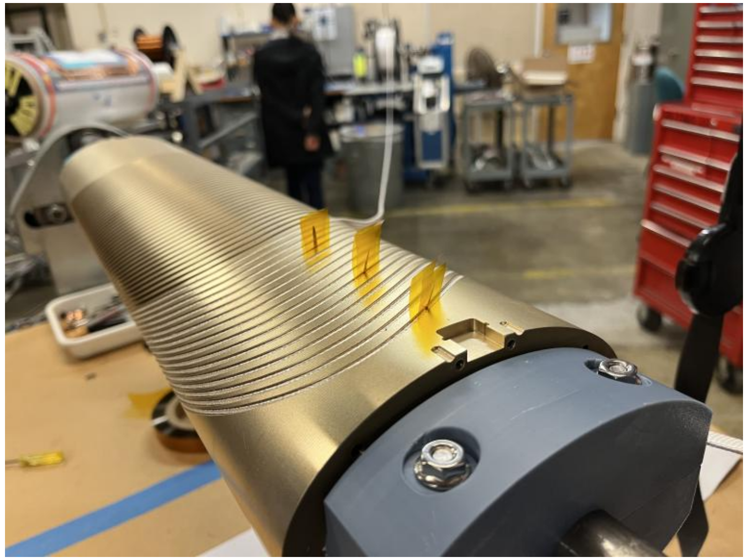
R. Norris
P. Mallon

Instrumentation (voltage taps with ~6 turn resolution)

Inner Layer

Outer Layer





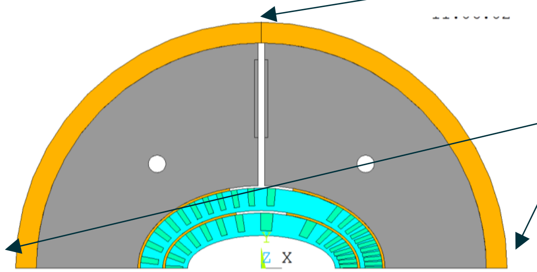
E. Buron

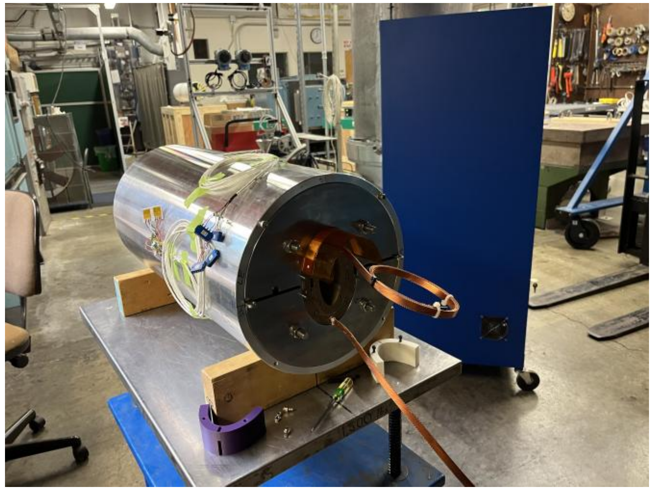
Instrumentation (strain gauges + field probe)

Strain gauge stations (HBM full bridge)

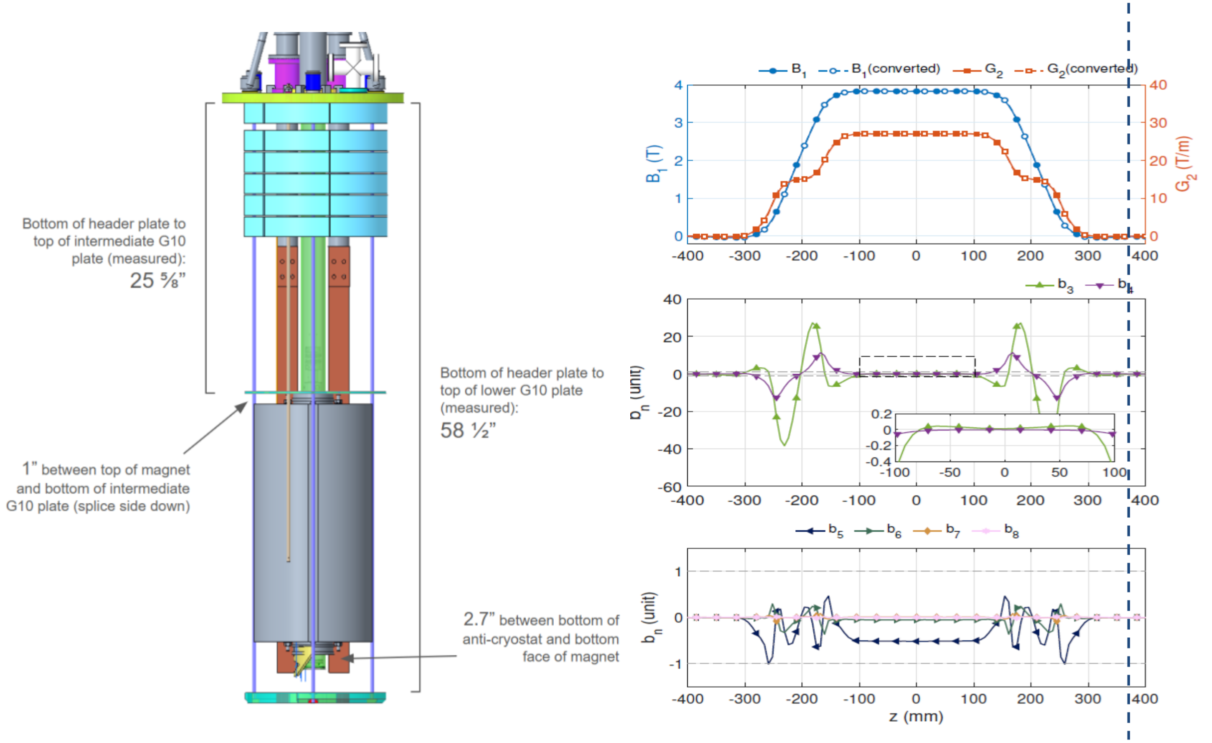
single pole (e_z and e_y)

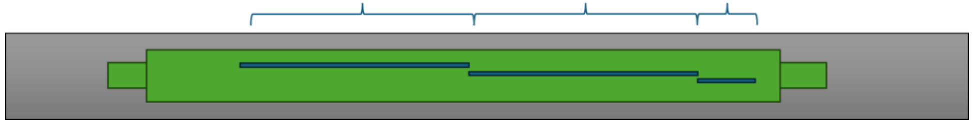
2x midplane (e_z and e_y)





New combined function rotating field probe for central and integrated field quality (J. DiMarco FNAL)





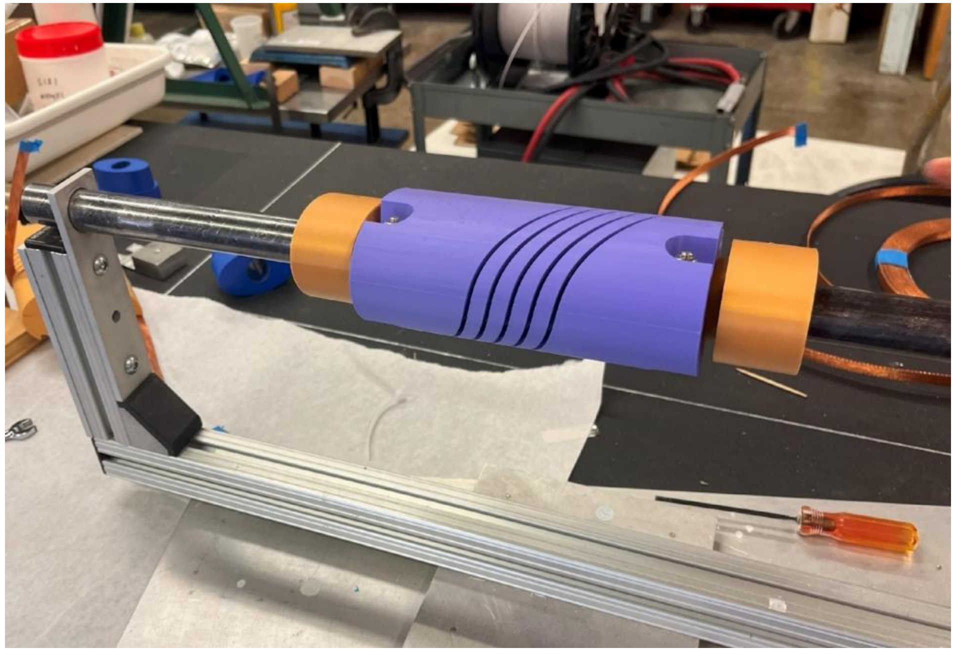
Status and next steps

- Design of a first ~5-6 T CCT magnet is complete with the goal of demonstrating combined function fields in an elliptic aperture
- We are about to complete the magnet assembly and begin test preparation
- We should be ready for a first 4.2 K test in ~1-2 months (actual test likely later due to LBNL test facility availability)
- In parallel we are beginning design of the next step (higher field Nb_3Sn design)

Thank you

3D printing is a helpful tool for winding tests with complex geometry

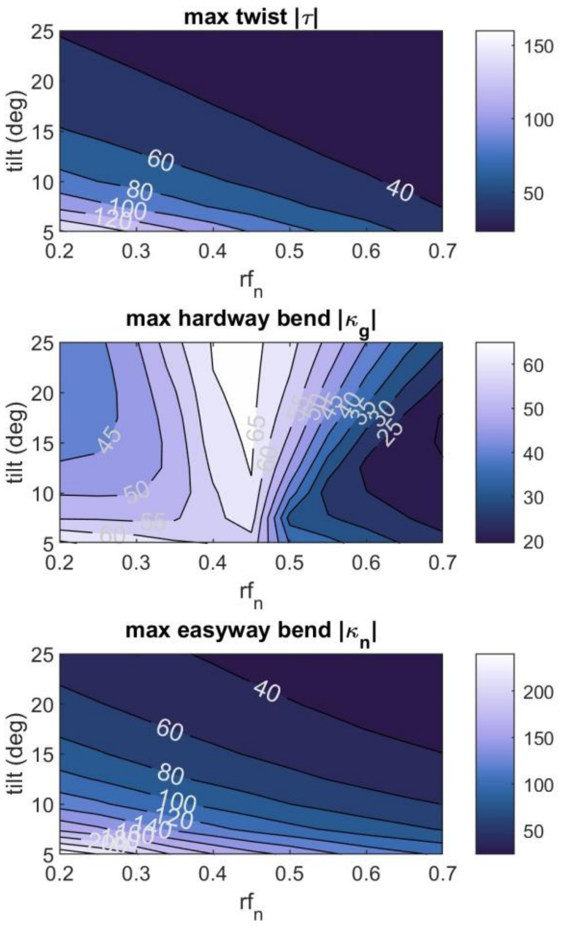
The starting point for us was to get an understanding of the windability limits for the 40 x 90 mm aperture and the chosen NbTi cable

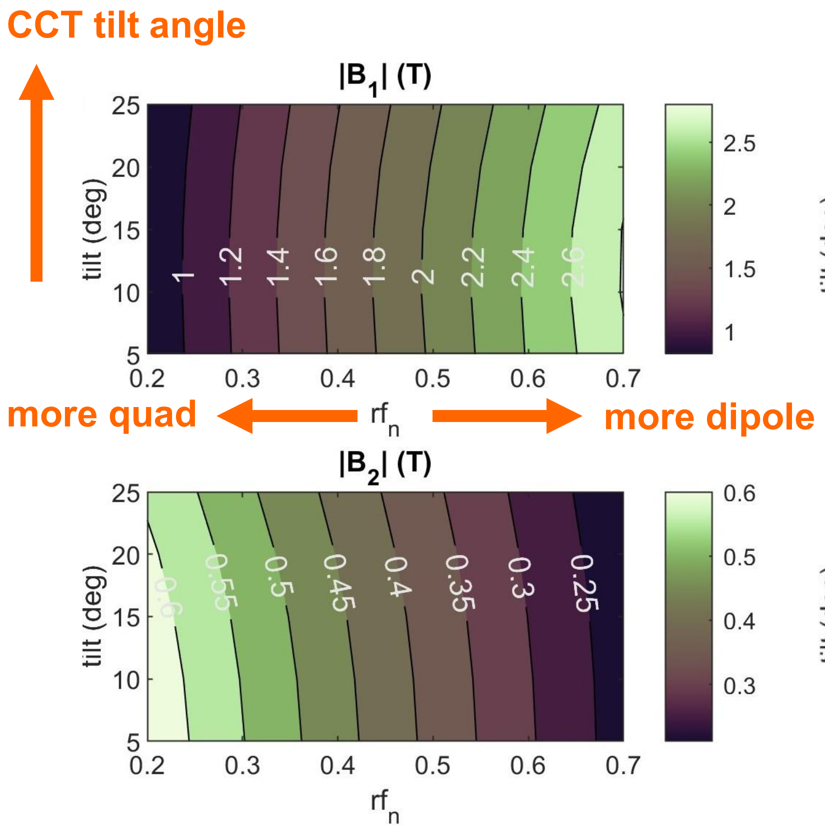


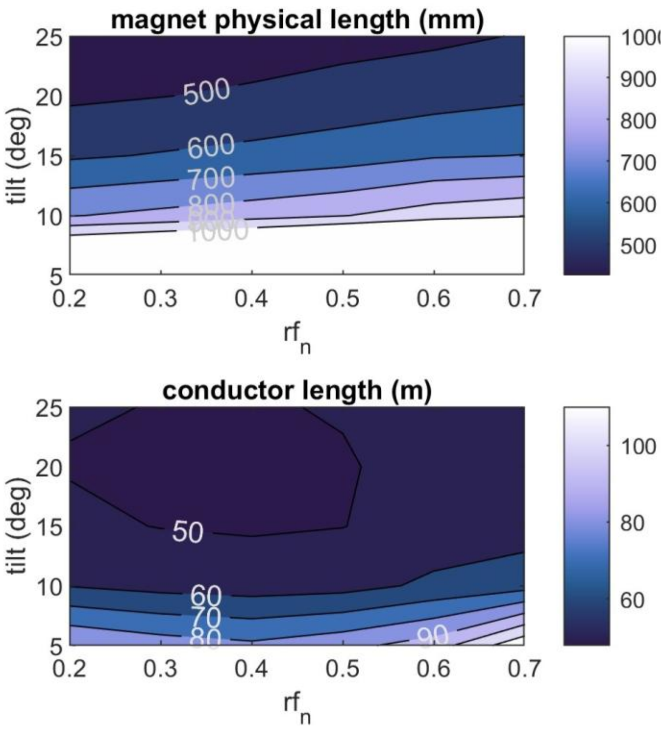
Summer intern Brian Palmer

We calculate the windabilty parameters using an approach similar to Roxie*, with this we can explore the parameter space of tilt angle and ratio of quadrupole to dipole fields

Ratio of dipole to quadrupole fields $rf_n = \frac{B_1}{B_1 + B_2(r = a)}$







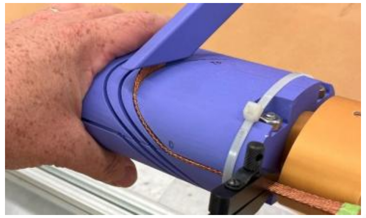
for 100 mm straight-section

*with some approximations for cases where the cable orientation deviates from the normal of the elliptic cylindrical surface

Work by Yufan Yan

Right now, our best correlation to windability is hardway bending

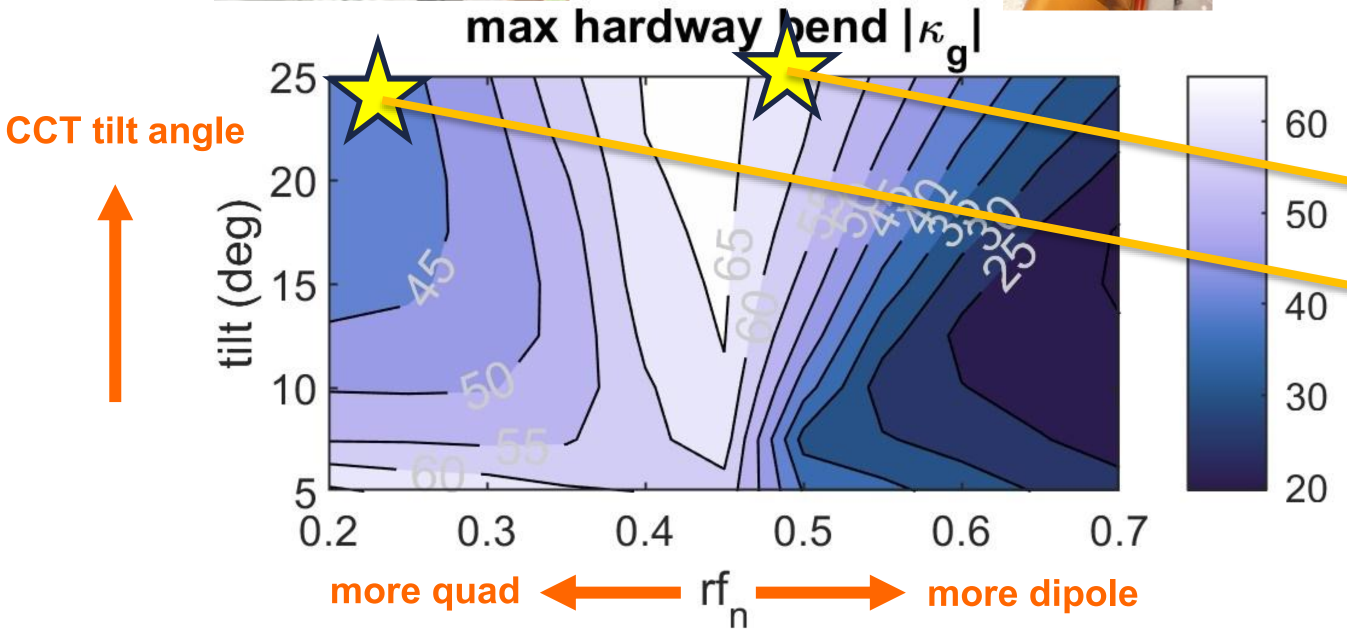
Test 3: too challenging at poles



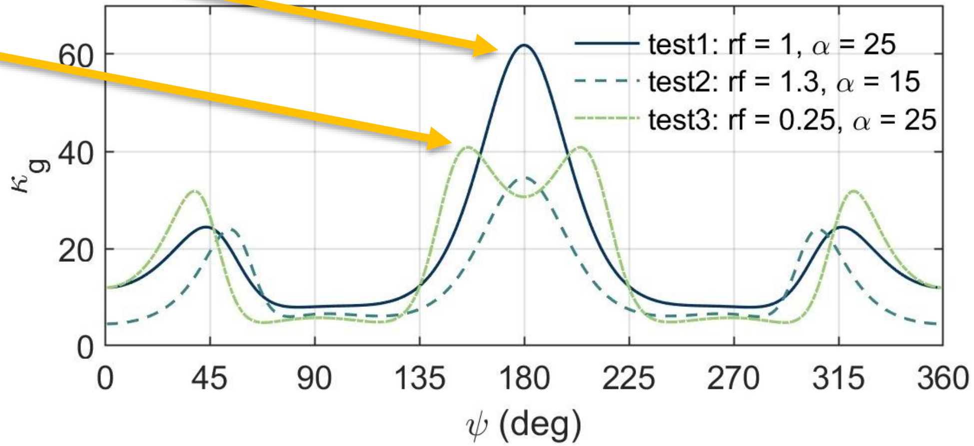
Test 1: not windable across major axis

Initial Conclusions

- Unlike CCT dipoles cases, better efficiency (lower tilt angle) can be easier to wind!
- Windability is worst where the ratio of dipole to quadrupole is 1:1



The trouble locations found during winding tests directly map to locations with highest hardway bending

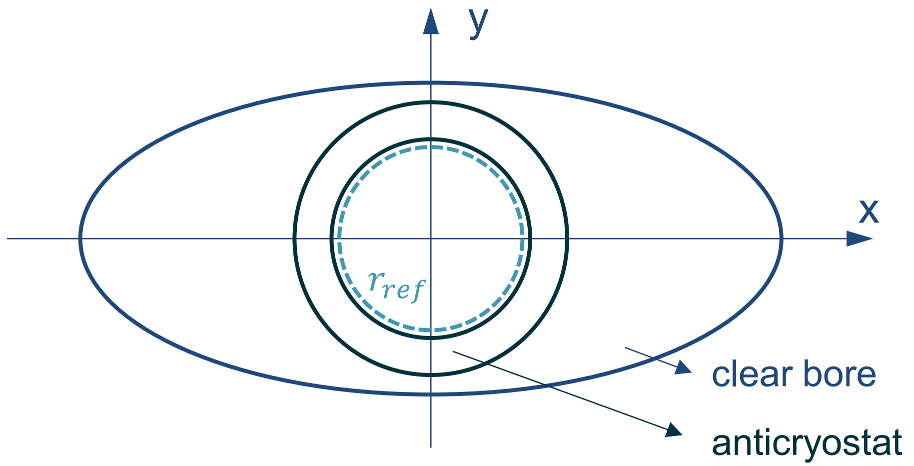


Plan for field measurements (circular coil)

BERKELEY LAB

Field measurement in LHe

- existing anticryostat: ID: 25.4 mm, OD: 35 mm
- reference radius: 11.75 mm
- bucking: dipole and quadrupole
- length: to measure harmonics distribution along z-axis; region with |bn| < 1 unit is about 200 mm



approximately to scale

Collaboration with Joe Dimarco at FNAL for combined function probe

Harmonics are normalized against
$B_{main} = |B_1| + |B_2(r = r_{ref})|$

Higher Order Harmonics at 10 kA are all < 1 unit

B_1 (T)	B_2 (T, @ r_{ref})	b_3	b_4	b_5	b_6	b_7	b_8	b_9	b_{10}
-3.811	-0.315	0.0933	0.0205	0.4786	0.0532	0.0065	0.0029	0.0018	6.66e-6
b_{11}	b_{12}	b_{13}	b_{14}	b_{15}	b_{16}	b_{17}	b_{18}	b_{19}	b_{20}
-0.0063	0.0067	0.0093	-2.42e-4	-8.60e-4	-0.0024	-3.51e-5	0.0056	9.65e-4	-0.0026

a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	a_{10}
-0.0853	-0.2878	-0.0342	0.0467	-0.0008	-0.0133	0.0065	-0.0044	-0.0111	-0.0057
a_{11}	a_{12}	a_{13}	a_{14}	a_{15}	a_{16}	a_{17}	a_{18}	a_{19}	a_{20}
0.0045	0.0054	-0.0068	-0.0080	-0.0042	-0.0030	0.0019	-0.0021	-0.0076	-0.0026

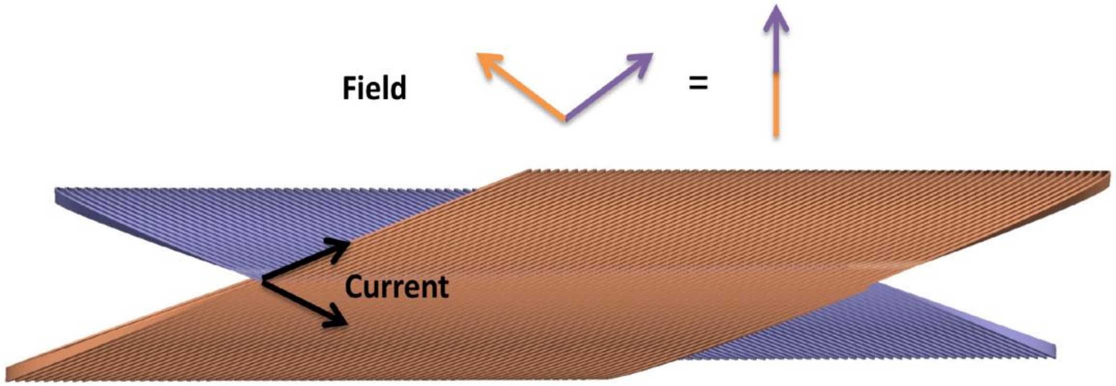
Canted-Cosine-Theta (CCT) SC Magnets

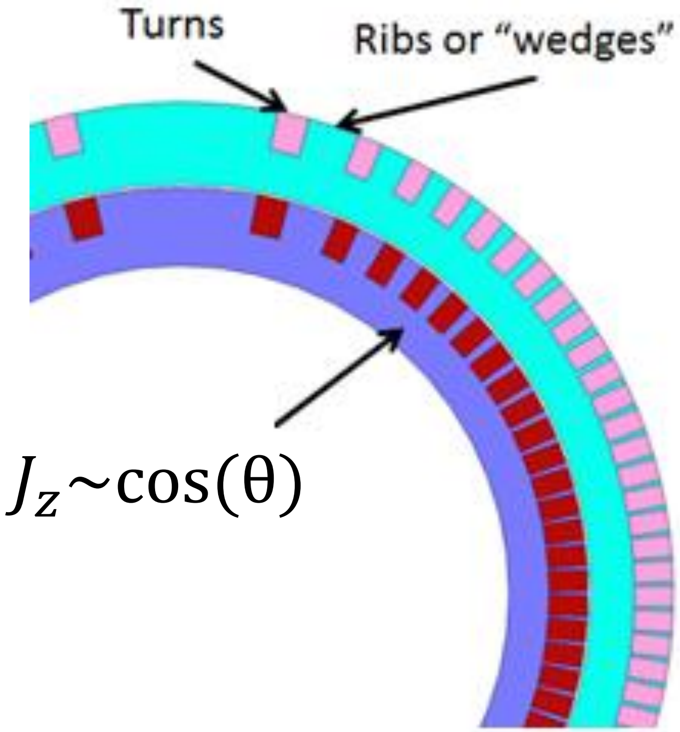
Advantages

- excellent field quality (to large % of aperture)
- stress management for high-field and/or large apertures
- combined function fields (i.e. dipole + quadrupole)

Challenges

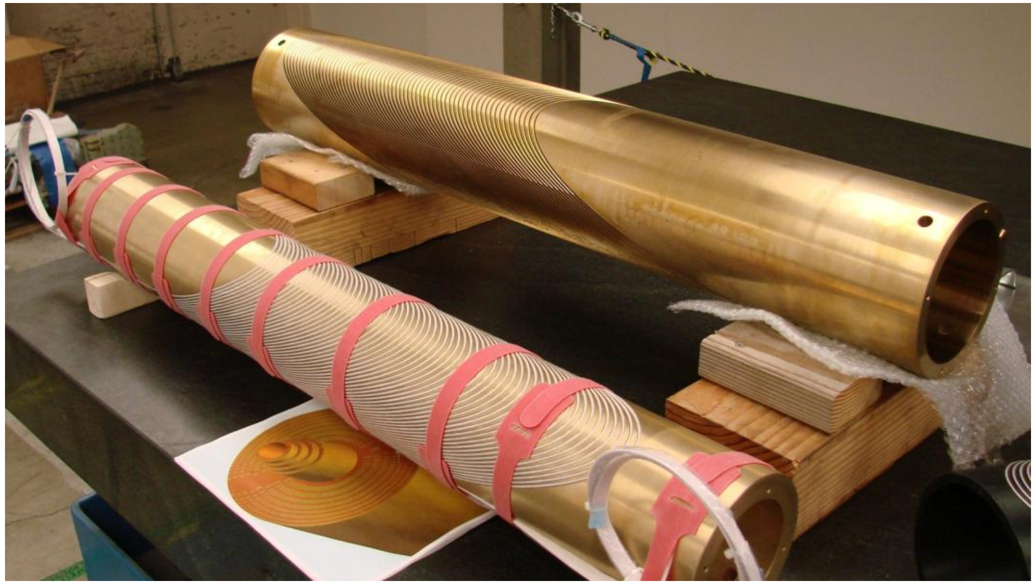
- slightly more conductor (~15-20%)
- tradeoff of longer ends vs. efficiency for very short magnets



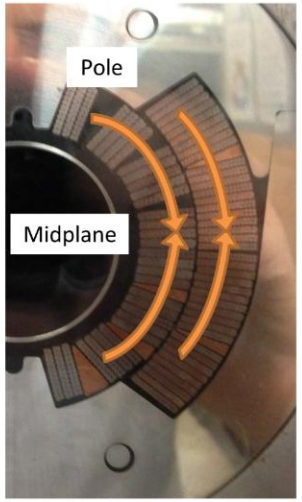


D.I. Meyer, R. Flasck, 1970, doi.org/10.1016/0029-554X(70)90784-6

Metallic Winding Mandrels Accurately Position the Conductor and Intercept Lorentz Forces for Stress Management



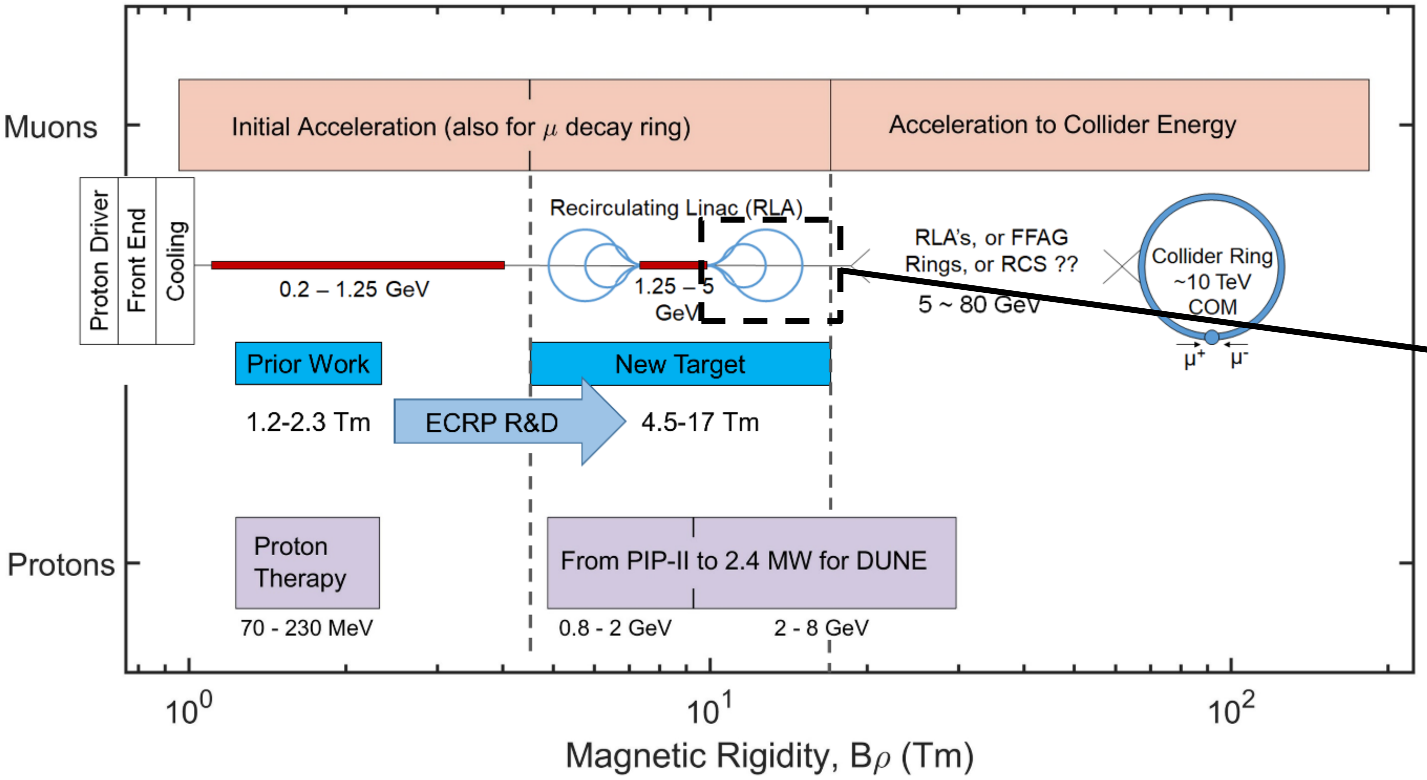
Force accumulation in traditional Cos(θ)



CCT ribs intercept force

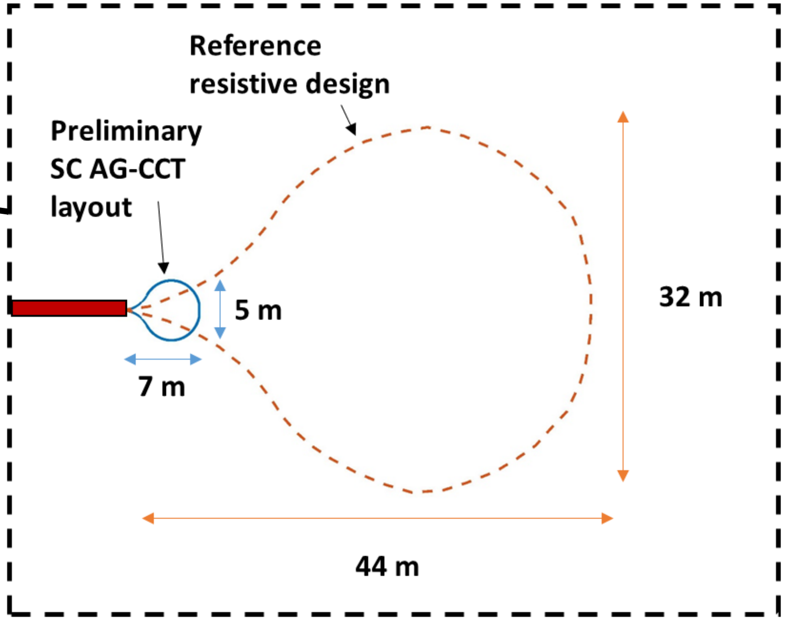
- Important for high field magnets with strain sensitive conductor (Nb_3Sn/HTS)
- Important for large aperture magnets

Superconducting magnets enable ultra-compact FFA layouts



Morozov, et al 10.1103/PhysRevSTAB.15.060101

SC magnets reduce footprint with (1) higher field and (2) a novel configuration achieving large momentum acceptance with minimal reverse bending



Preliminary scoping with superconducting magnets leads to a compact layout for a 1-5 GeV/c muon RLA (1.7 T, 87 T/m, 100 mm aperture)