GigaBREAD Mechanical Design

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1/14/26

BREAD COLLABORATION

GigaBREAD

What is GigaBREAD:

- Pilot version of BREAD experiment searching for dark photons and axion-like dark matter signals in the 10-15 GHz microwave band using a broadband reflector and horn antenna readout
- Axion-induced photons generated at cylinder boundary and focused onto horn antenna focal spot
- $E_a(t) \propto B_e, 1/\varepsilon, 1/\mu$

Scope of this talk:

- Mechanical design updates (red arrows)
- COMSOL multiphysics simulation updates
- Next steps

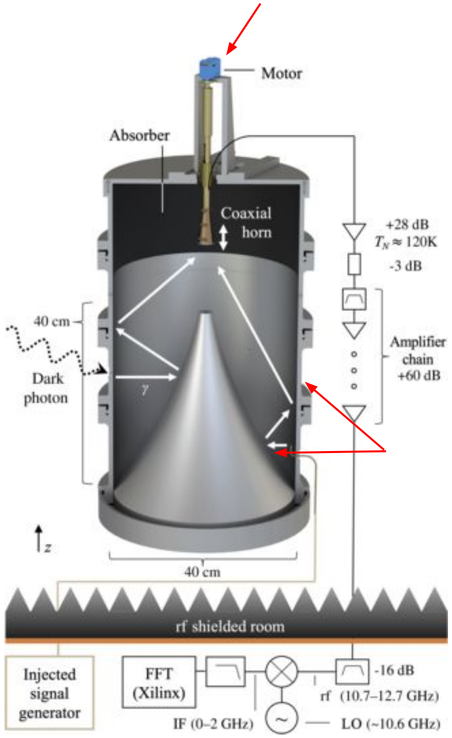


Fig 1: Schematic of previous larger BREAD design

[1] Phys. Rev. Lett. 132, 131004 – Published 28 March, 2024

Mechanical Design Challenges

- Precise motor control for optimal antenna placement
- Structures must withstand magnet quench forces
- Maximize axion-photon conversion efficiency; minimize losses
- Must operate in cryogenic temperatures and withstand thermal cycling

Why we need a motor

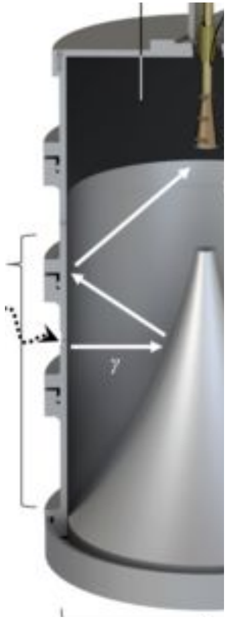


Fig 2: Photon optical path leading to standing waves

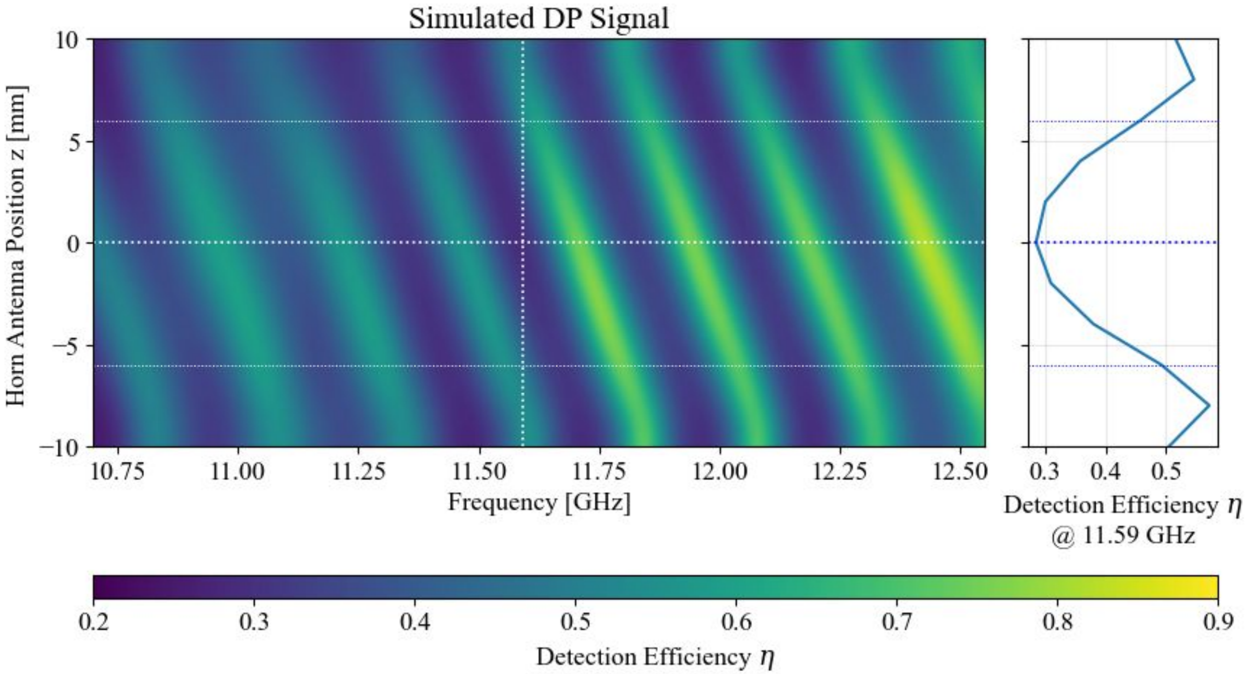


Fig 3: Simulated signal detection efficiency vs. horn antenna position and frequency. Bands indicate constructive and destructive interference. Prior BREAD design parameters; simulation by Stefan Knirck.

DP Signal (+/- 10mm travel range) - Dataset: 2023-06-27-axionsignal-opti=1.txt

Motor Requirements

- Cryogenic and UHV compatible, non-magnetic actuation
- Precision motion, >10 mm travel with feedback
- >10N load capacity (horn antenna assembly) & self locking
- Compact form factor

Fig 4: Horn Antenna (Mass = 0.6 kg)

Motor Selection: JPE CLA2602

- Cryogenic range: 20 mK | Travel: 12 mm (6mm w/ COE)
- Driving force: **40 N @ 4K** | Holding force: 100N (self-locking)
- Stepping: 5 nm @ 4K
- Optical encoder: 850 pulses/rev = 294 nm axial displacement
- Stick-slip principle: voltage ramp (stick) → rapid voltage (slip)

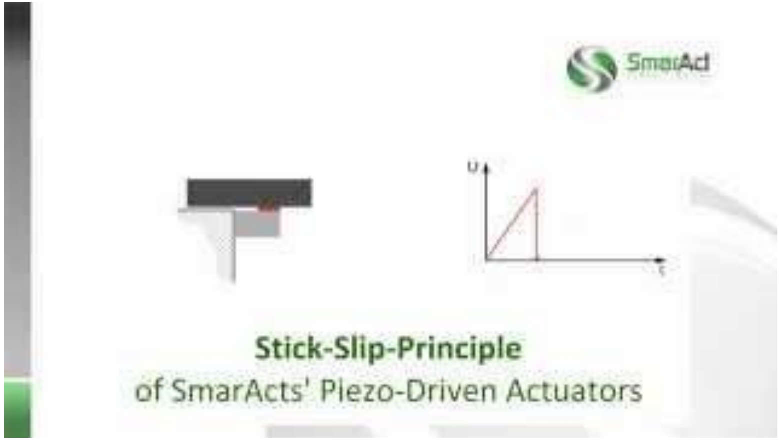


Fig 5: JPE CLA2602 Cryo Linear Actuator (Taken from JPE)

Motor Testing - Total Travel

Total travel ~20mm

- No hardware endstops or safeties in place
- At one end thread completely detaches from nut
- At other end rotating motor head presses against plastic flange - stalling motor
- Effective travel with given nut length ~ 13.7mm
- Can design our own nut to increase travel distance!

Acknowledgments: Motor and linear stage courtesy of G. Carosi (LLNL)

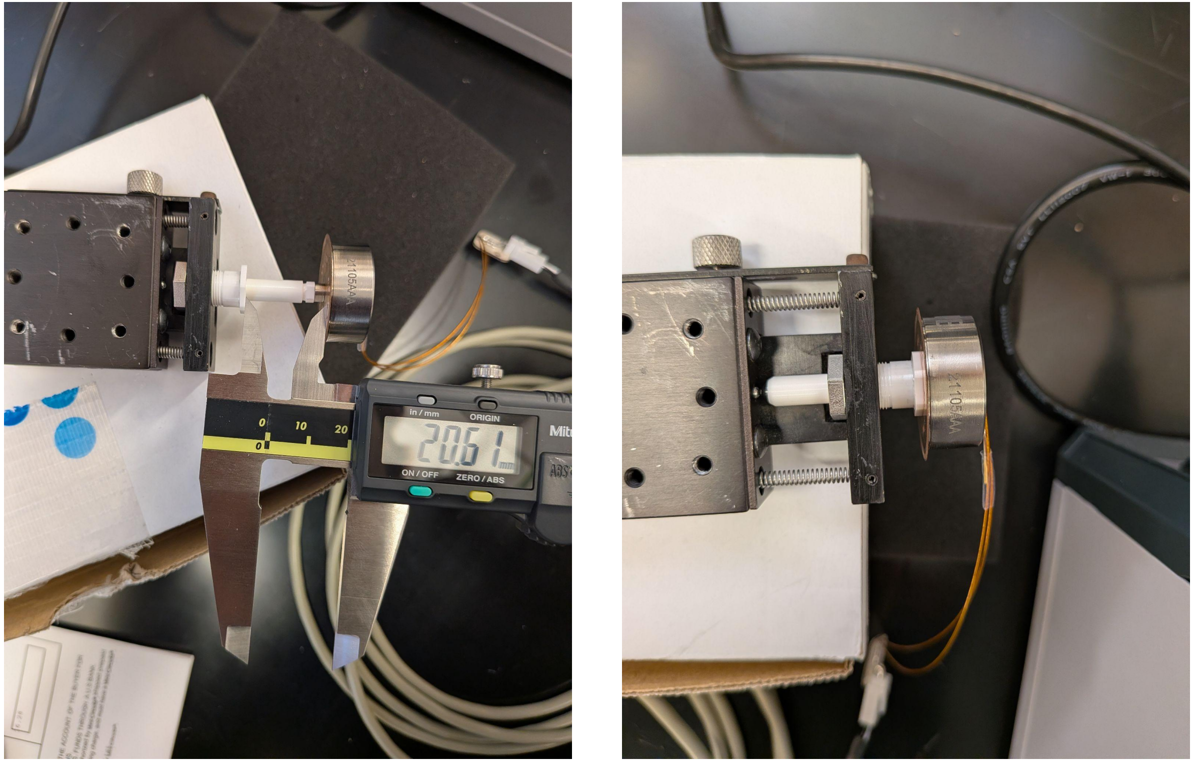


Fig 6: JPE CLA2602 motor travel testing.

Motor Testing - Load Capacity (@ 295K)

Two lead disk weights added at room temperature

Disk 1: 3.25 lbs (~1.5 kg) ✓

Disk 2: 6.5 lbs (~3 kg) ✓

Total weight: 9.75 lbs (~4.5kg) → 43 N ✓

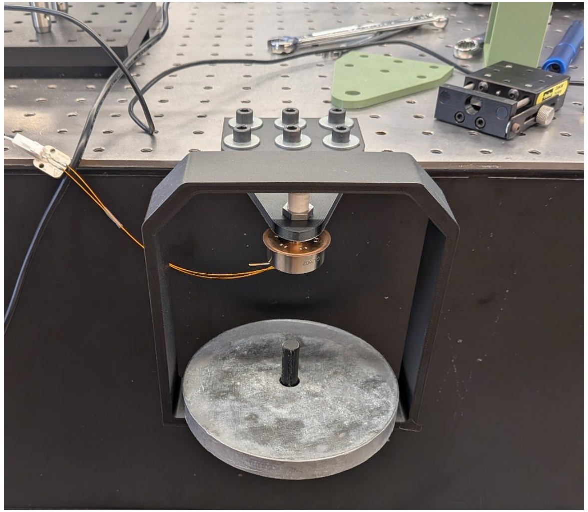


Fig 7: Motor load testing

Motor Testing - Load Capacity (@ 4K)

Results - TBD

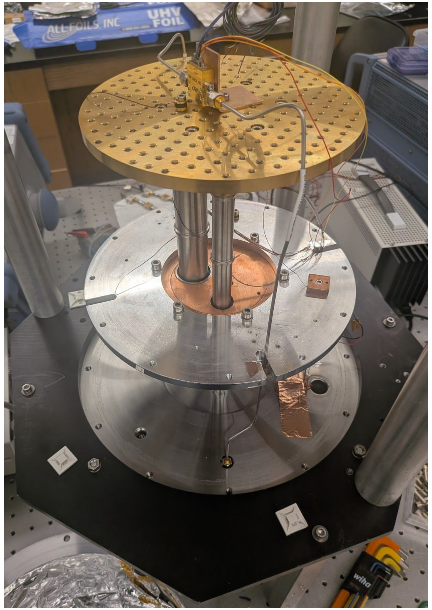


Fig 8: 4K cryostat being used for cryo load testing

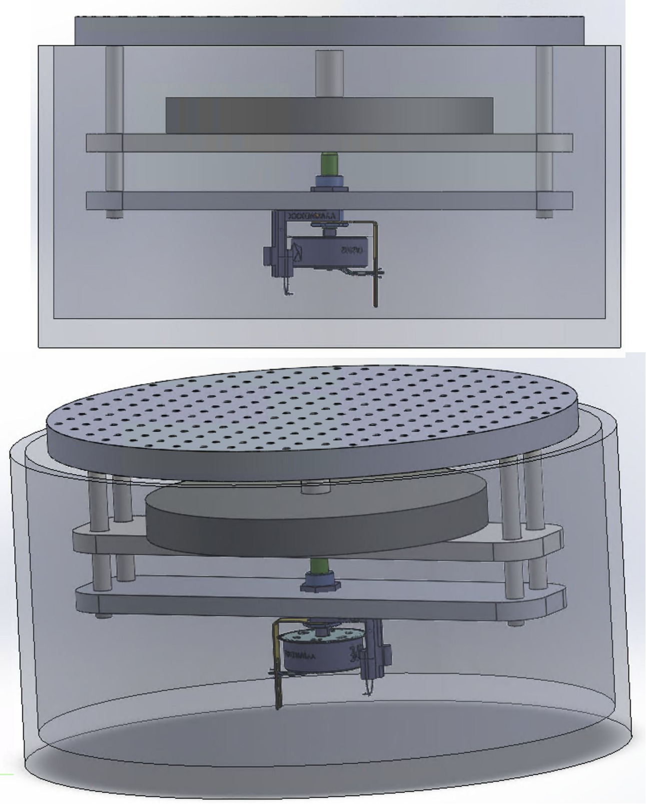


Fig 9: 4K motor load test CAD assembly

Motor Testing: Summary

- Functionally verified at room temperature (both directions)
- Effective travel: 13.7mm with stock nut (can be increased)
- Load capacity at room temperature: > 43 N
- Next: Load testing at cryogenic temperatures

Motor Assembly Design Iterations

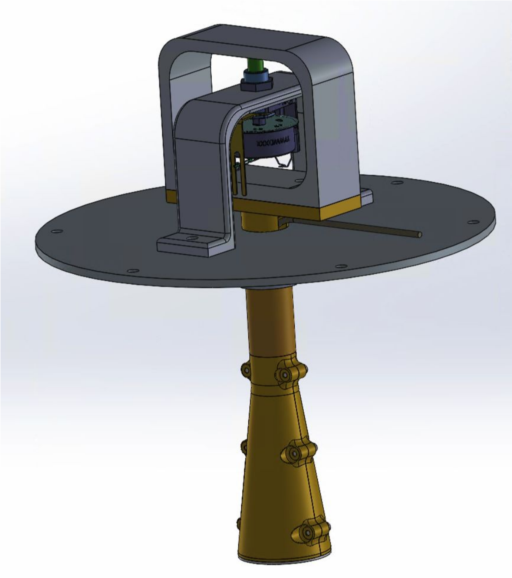


Fig 10: v0 preliminary motor assembly design

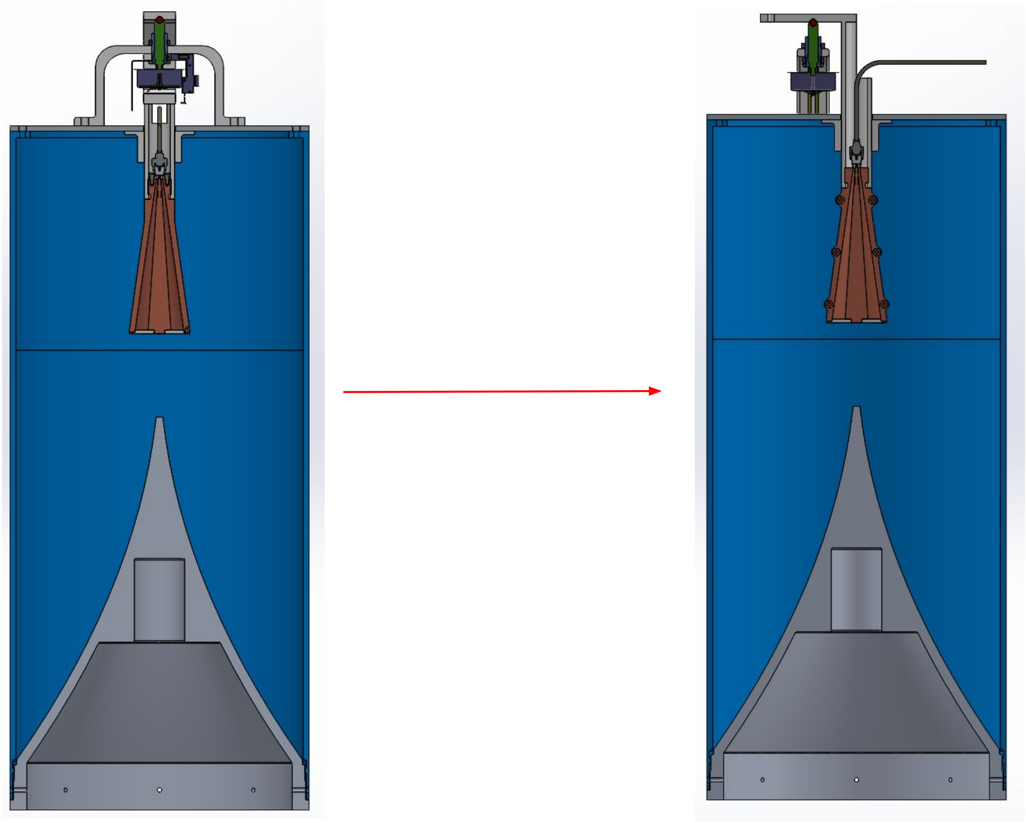


Fig 11: Cross section of GigaBREAD assembly design iterations. Motor moved off axis due to SMA feedthrough interference

Motor assembly integrated into fridge

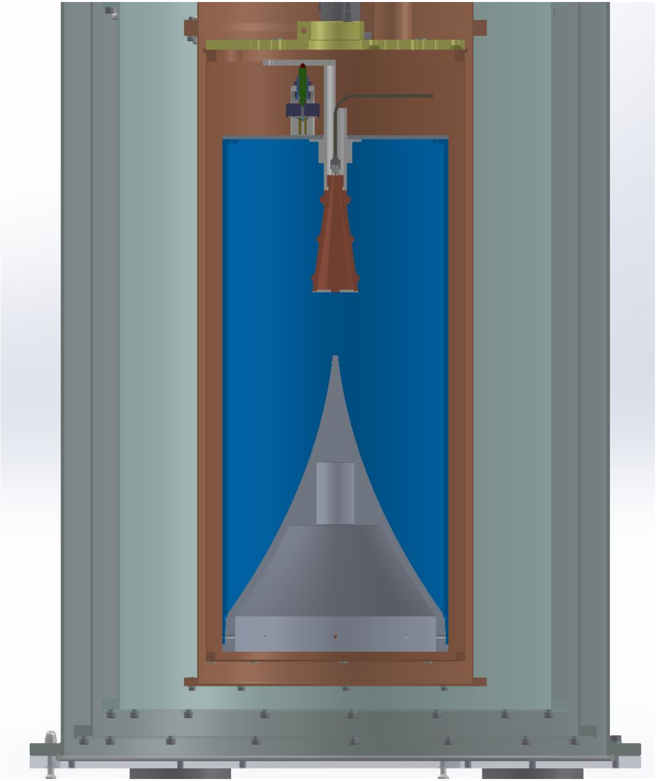


Fig 12: Cross section of GigaBREAD assembly integrated in the ProteoxS dilution fridge.

COMSOL Multiphysics Simulation

Reflector/barrel design constrained by worst-case loading scenario: magnet quench

- Magnet Quench: 4 T/s field collapse → eddy currents → large Lorentz forces
- Coupled Physics: Eddy currents → EM Joule heating → material property changes
- Design Validation: Compare stresses vs. yield strength limits (COMSOL Multiphysics)

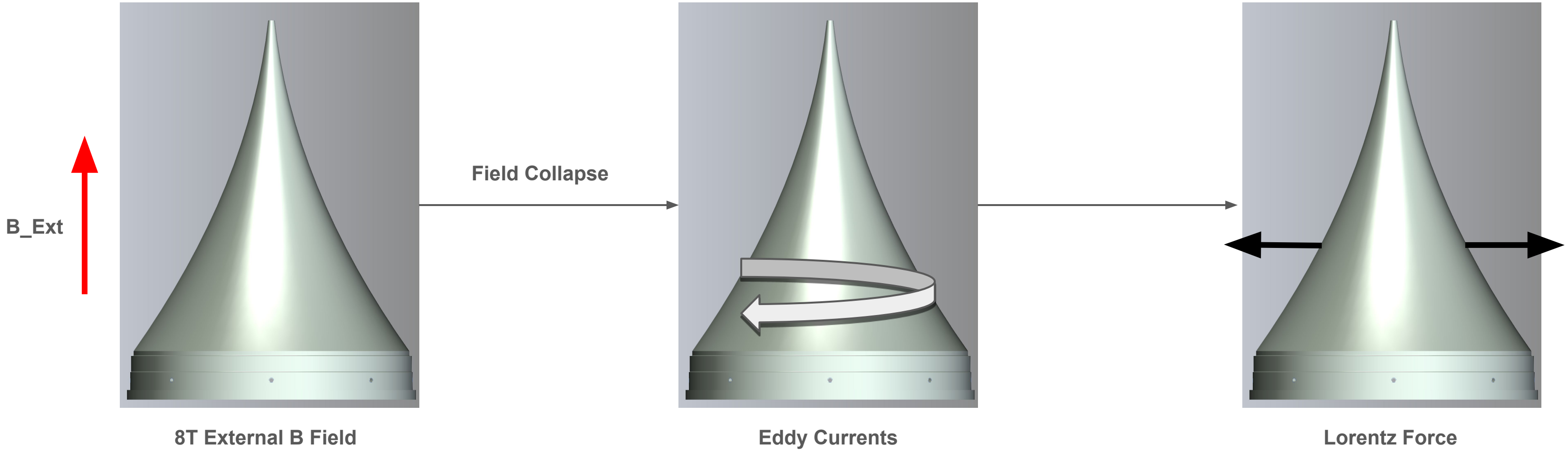


Fig 13: Representation of magnet quench resulting in Lorentz force

Magnet Simulation

Reconstructing Oxford Instruments Magnet Analytically

Design Target 8T @ Central axis

Optimized parameters:

Outer Coil:

- Radius 0.248m
- Length: 0.551 m
- Number of turns: 21310
- Current: -120 A

Inner Coil

- Radius: 0.1003
- Length: 0.2903
- Number of turns: 5452
- Current: 120A

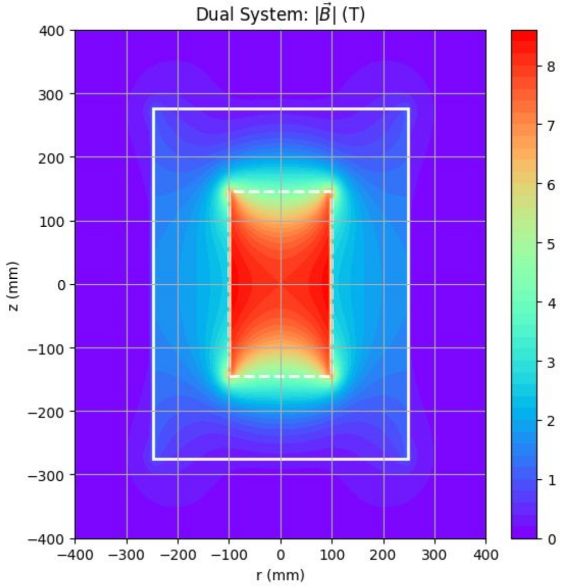
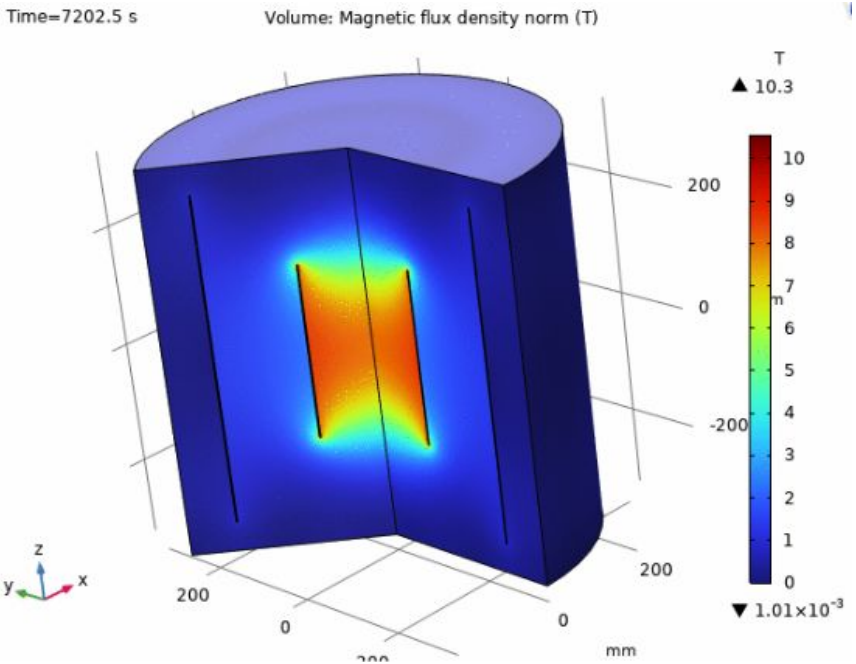


Fig 14: Simplified two-coil model optimized for 8T on-axis with minimal external field. Winding data from this model was used in COMSOL simulations

Credit: Jasmine Palma

COMSOL Validation: B-Field mapping w/o and w reflector



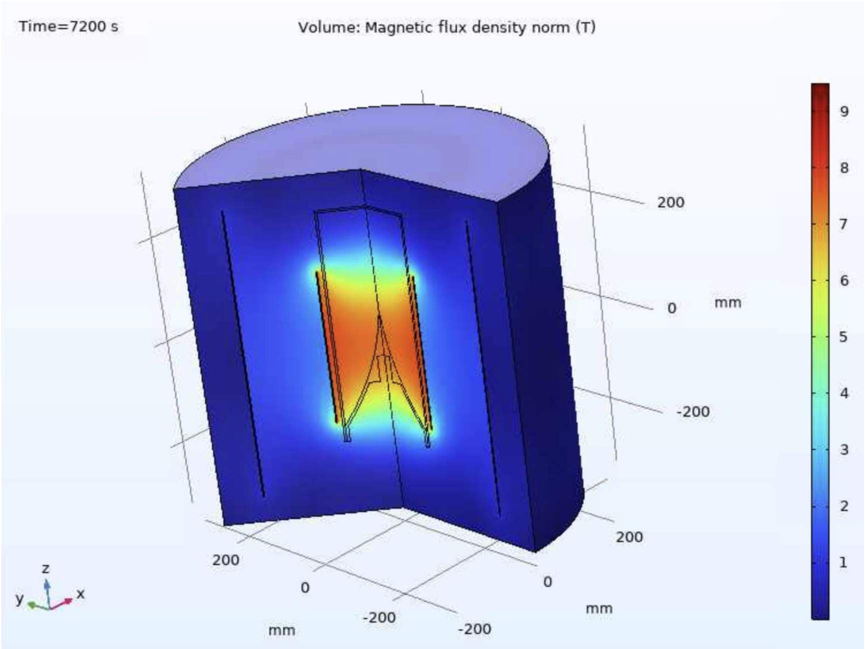


Fig 15: Parameters from previous analytical solution validated in COMSOL w/o and w/ reflector

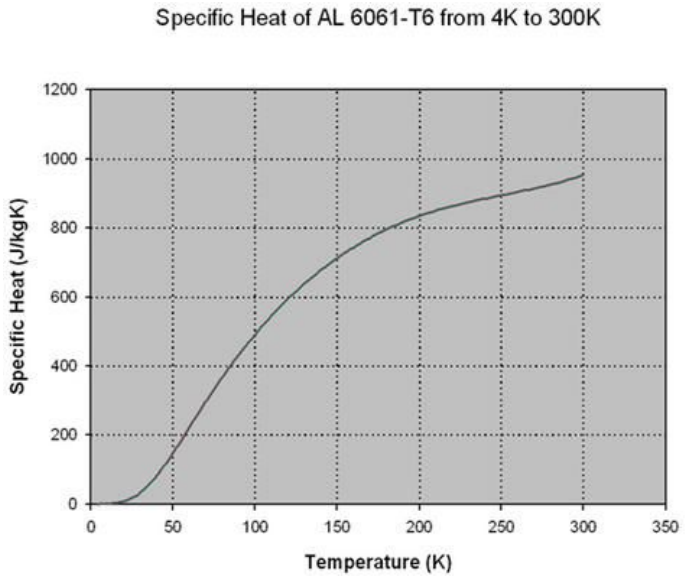
Thermal Simulation

COMSOL: Heat Transfer Module

- Heat Equation: transient temperature evolution with source Q
- Heat Transfer mechanisms: conduction, convection, radiation
- Thermal Expansion: temperature-dependent CTE induces mechanical strain
- GigaBREAD: conduction + radiation dominant; quench heating from Joule losses
- Coupling: temperature → structural mechanics (material properties & thermal stresses)

Temp Dependent Material Properties

Temperature dependent properties applied to simulation (taken from NIST)



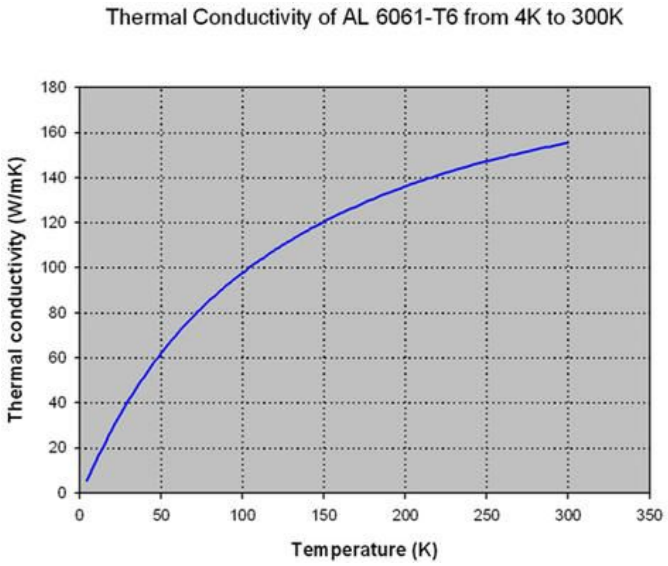
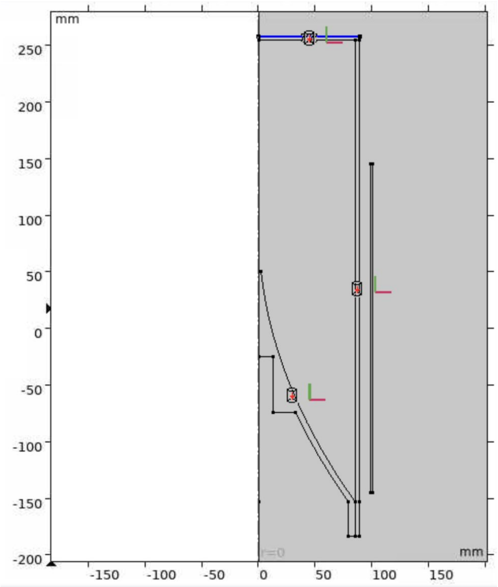


Fig 16: NIST derived temp dependent material properties for 6061-T6 Al

ProteoxMX Cooling Power Applied

Heat Flux applied to top plate based on ProteoxMX specifications.



Key Specifications

Base temperature	< 10 mK
Cooling power at 20 mK	> 12 μW
Cooling power at 100 mK	> 450 μW
Sample space diameter	360 mm plate
Line of sight access	1 x Secondary Insert (117 mm x 252 mm), 2 x KF40, 2 x KF25
PTR options	1.35 W, 1.50 W or 1.80 W
Temperature control range	10 mK to 30 K with magnet at full field
Magnet options	Solenoid: up to 14 T Vector rotate: up to 9,1,1 T Field cancellation: < 10 mT

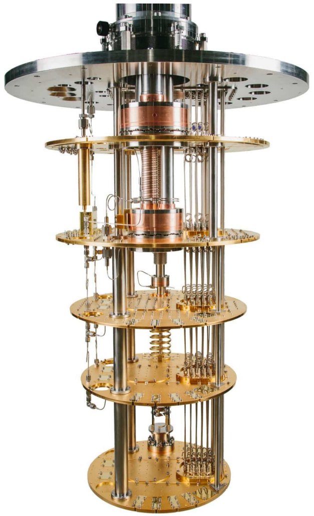


Fig 17: (Left) Cooling power applied to top surface, (Middle) ProteoxMX specs, (Right) ProteoxMX dilution fridge

Magnet Quench (Thermal Sim Results)

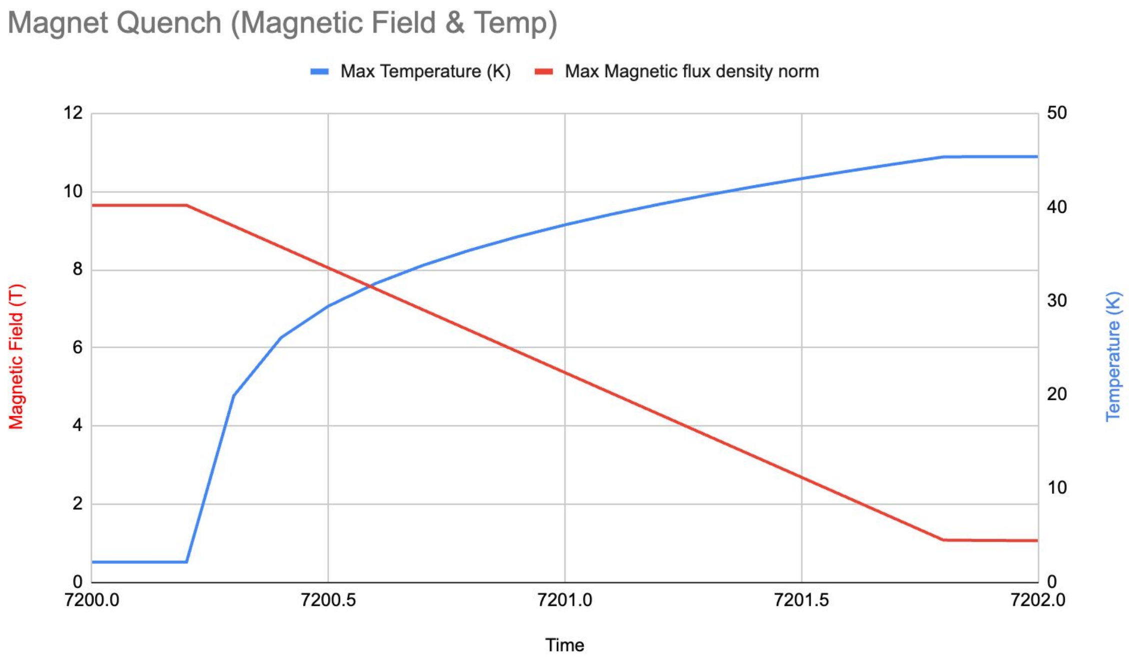
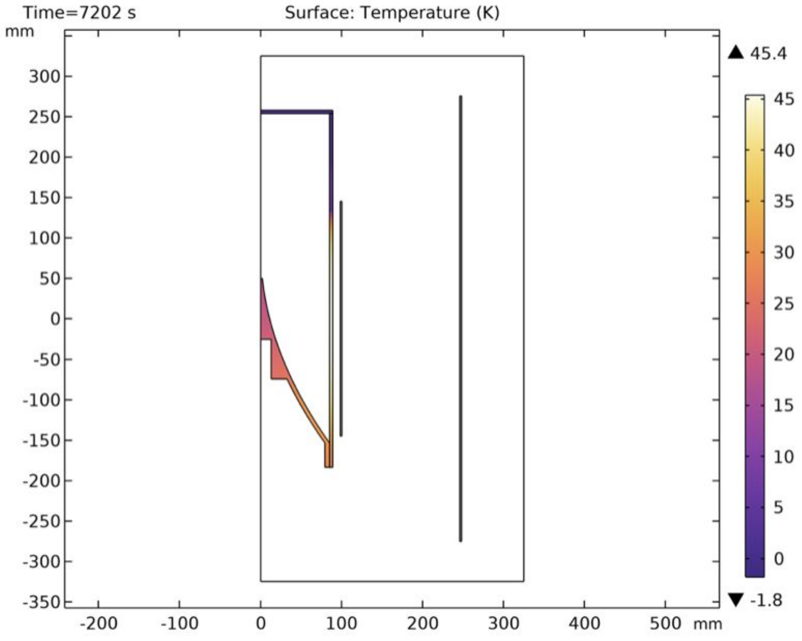
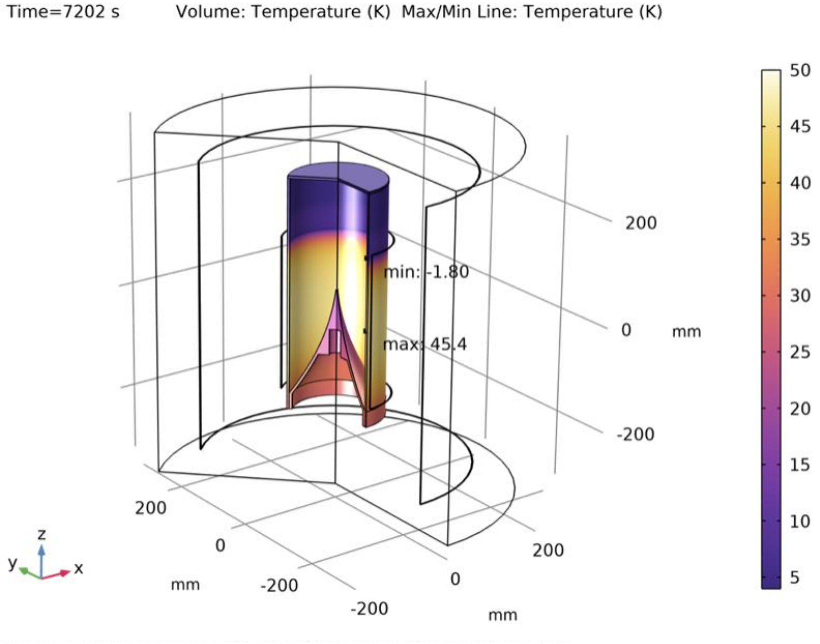


Fig 18: Plot of simulated max magnetic field and temperature during quench

Temperature (ht)



Surface: Temperature (K)



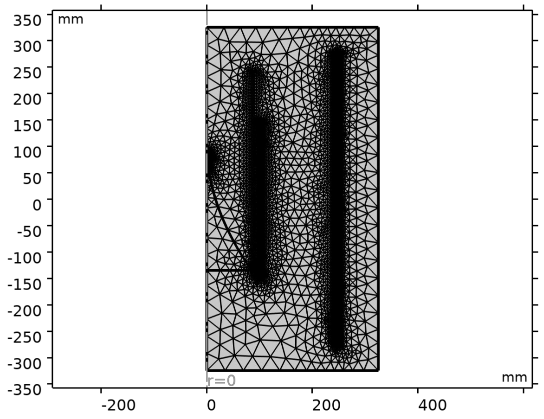
Volume: Temperature (K)

Fig 19: (Left) 2D plot of maximum reflector/barrel temperature (Right) 3D plot of maximum reflector/barrel temperature

Mechanical Simulation

COMSOL: Structural Mechanics Module

- Finite Element Analysis: discretize geometry into elements
- Stress-Strain: material constitutive models (elasticity, plasticity)
- Boundary Conditions: constraints, loads, gravity
- Output: displacement field, stress tensor (σ_{xx}, σ_{yy}, σ_{zz}, shear)
- GigaBREAD: stresses in cylinder/reflector under Lorentz forces (quench)



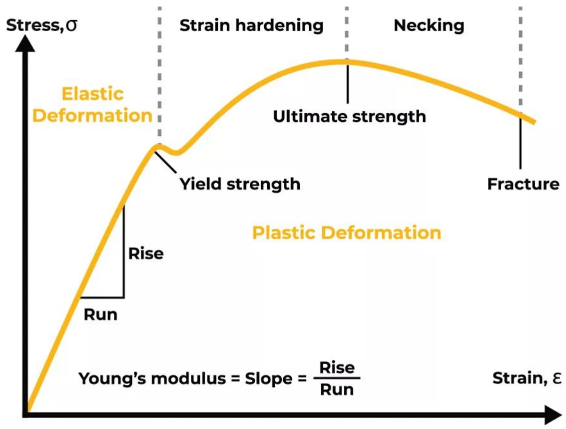


Fig 20: (Left) Example of mesh used in FEA analysis (Right) Typical stress strain curve for ductile materials (taken from Ansys)

COMSOL: Structural Mechanics Module Inputs

- Fixed constraint applied to top plate surface - rigidly connected to mixing plate
- Lorentz force body load applied to reflector and barrel
- Temp-dependent Young's Modulus (NIST)

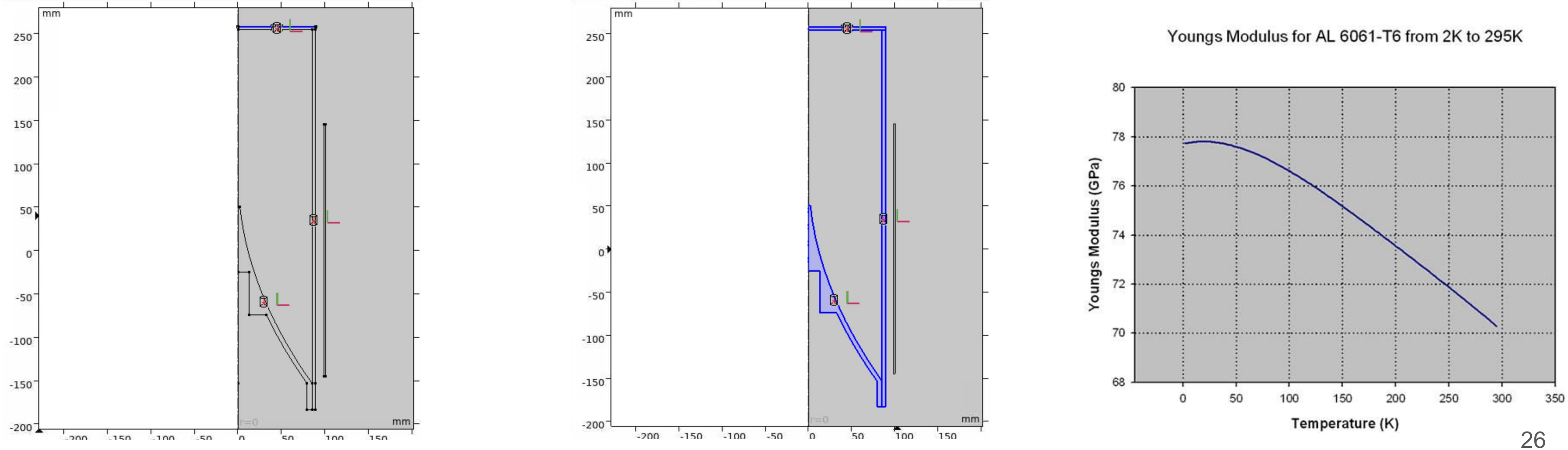


Fig 21: Comsol structural mechanics inputs. (Left) Rigid connection to mixing plate (Center) Lorentz force body load applied (Right) Temp-dependent Young’s Modulus for 6061-T6 AL (taken from NIST)

Design Iteration 1: Solid Reflector

Result: Exceeded yield strength

- Al 6061-T6: Max von Mises Stress > σ_yield
- 316L Stainless Steel: Max von Mises Stress > σ_yield

Conclusion: Solid design not feasible

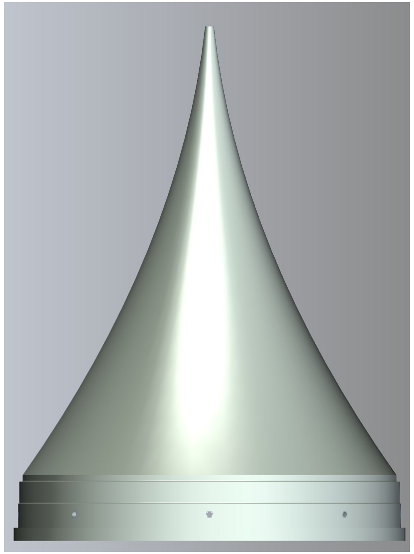


Fig 22: Preliminary solid reflector design

Design Iteration 2: Hollow Reflector

Results: Well within Yield Strength (Al: SF=3)

- Al 6061-T6: 131 MPa (barrel), 125 MPa (reflector) | σ_yield @ 4K = 350 MPa ✓
- 316L SS: 40 MPa (barrel), 41.5 MPa (reflector) | σ_yield @ 4K = 650 MPa ✓

Fig 23: Modified hollow reflector design reduces thermal mass and lorentz forces

Design Iteration 3: Cut Reflector and Barrel

- To further reduce eddy currents, we will wire EDM cut the reflector and barrel
- CMM measurements before and after will be performed to ensure no deformation

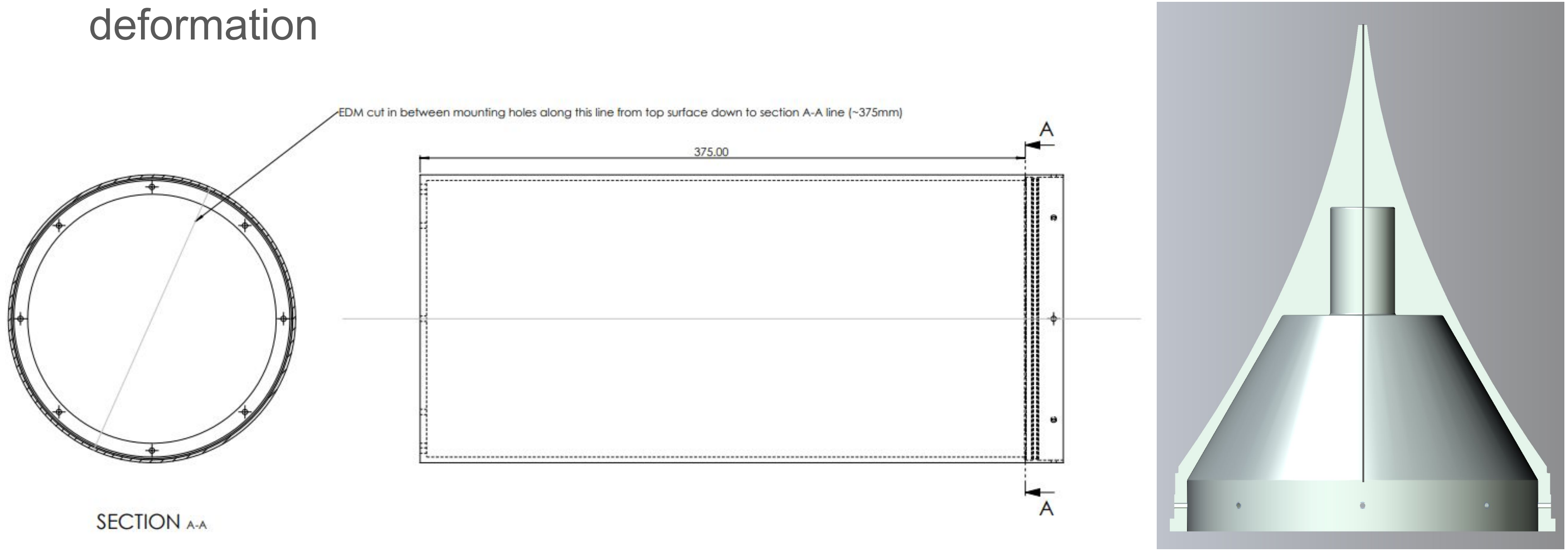


Fig 24: Modified barrel (left) and reflector (right) design. EDM cut to reduce forces

GigaBREAD in ProteoxS Dil Fridge

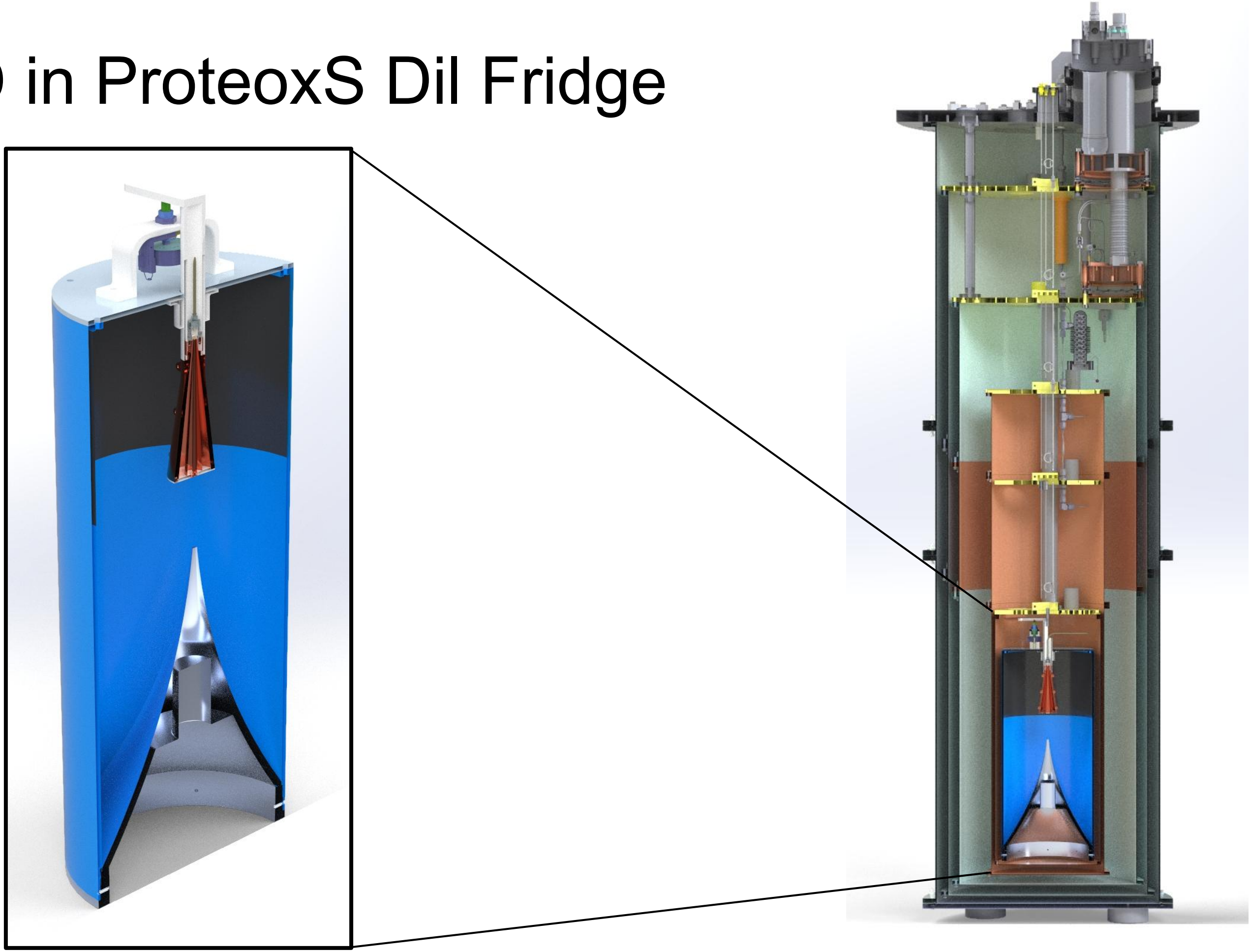


Fig 25: Integrated barrel and reflector into dilution fridge rendering. Absorber in black added to reduce stray light

Initial Parts

Fig 26: Initial prototype parts machined out of 6061-T6 Al

Next Steps

- Complete load capacity testing of motor at cryogenic temperatures
- Determine if reflector is at risk of going superconducting in phase space of operation
- Perform EDM wire cutting of parts and compare CMM measurements
- Refactor mechanical design for ProteoMX
- Develop motor heat rejection strategy
- Finalize GigaBREAD design and material selection

Thank You!

Questions?