Superconducting Magnetic Bearings for a High-Speed Electric Aircraft Motor

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Stuart Wimbush and Rod Badcock

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VICTORIA UNIVERSITY WELLINGTON
TE WHARE WĀNANGA O TE ŪPOKO O TE IKA A MĀUI

Acknowledgments

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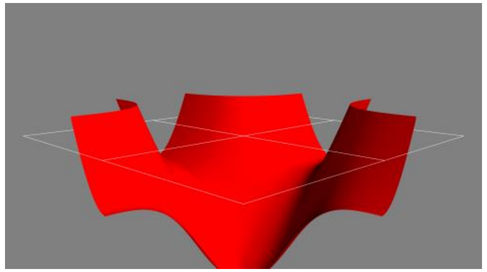
High-Temperature Superconductivity at Robinson Research Institute

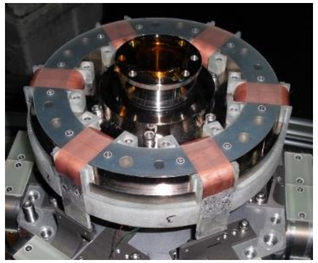
Fundamental → Applied

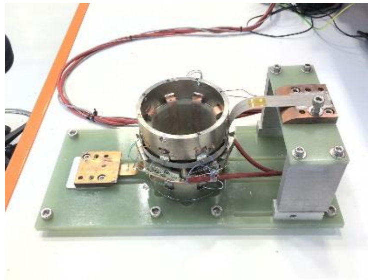
HTS physics



Wire development & characterization

HTS dynamos

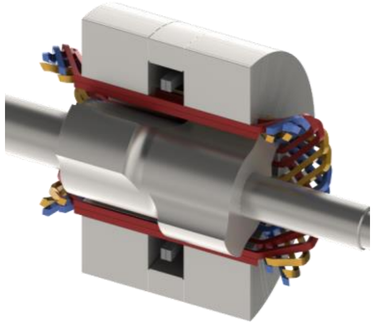


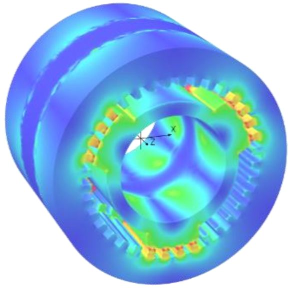


HTS transformer

HTS MRI

HTS motors & generators



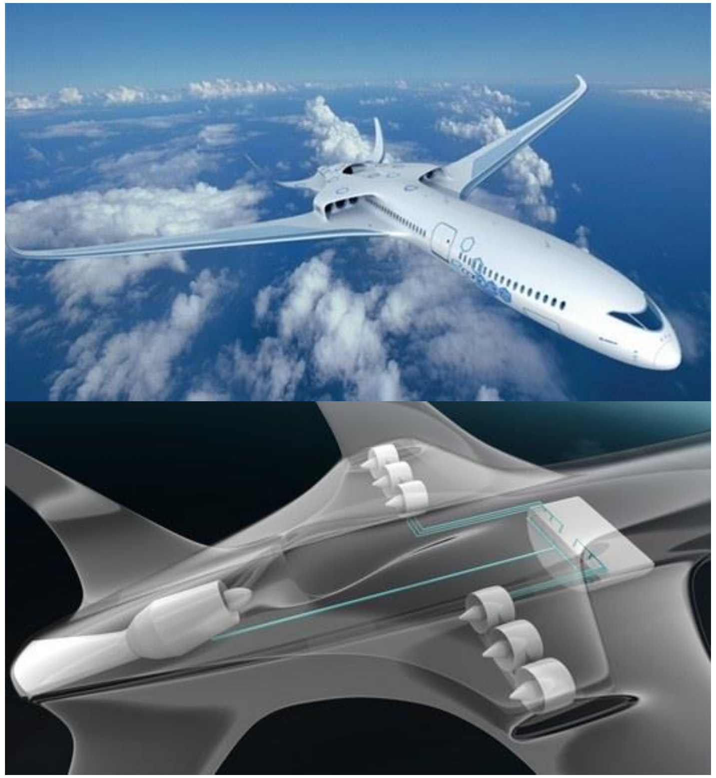


Background

Year 2 of 5 year programme: "Ultra-high speed superconducting machines for hybrid-electric aircraft"

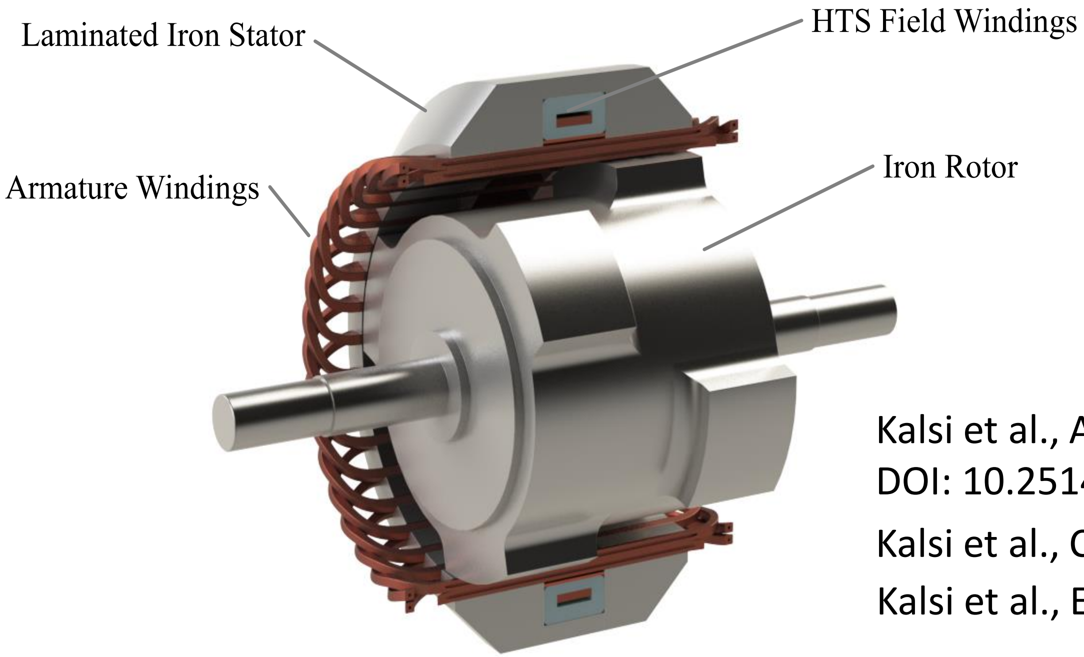
A. New concept HTS machine designs including: AC Homopolar, induction and wound-rotor architectures.
   - Design concepts completed.
   - Selecting demonstration machines now
B. Novel subsystem components including: Flux pump exciters, HTS bearings, quench detection, and high-saturation-field soft ferromagnets.
C. Computational tools to model and predict superconducting AC loss in ultra-high speed HTS machines.
D. Lab scale prototype HTS 10 kW motor operating at > 20,000 RPM.
   - Planned for year 4/5

Hybrid-Electric Aircraft



https://www.wired.com/2013/07/eads-ethrust-hybrid-airliner/

2 MW 25000 RPM Superconducting Homopolar Motor/Generator



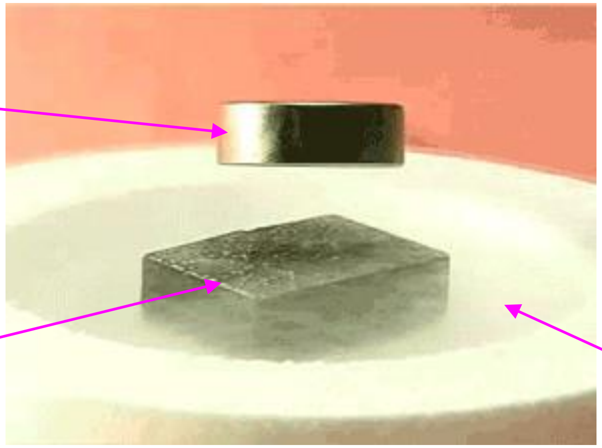
Kalsi et al., AIAA 2019-4517
DOI: 10.2514/6.2019-4517

Kalsi et al., CEC-ICMC 2019, M2Or4A-02

Kalsi et al., Energies 12, 86 (2019)

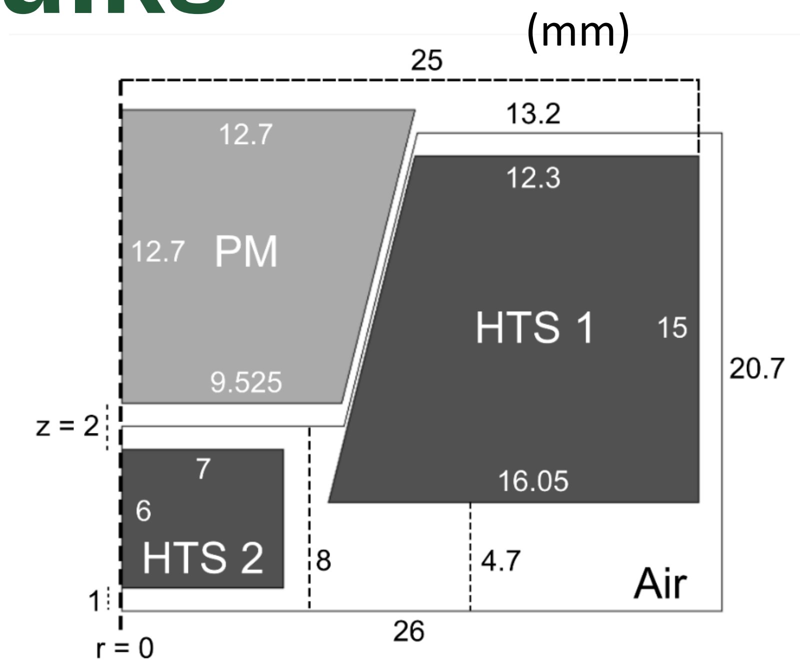
Require frictionless non-contact magnetic bearings since mechanical bearings would not be able to operate continuously due to frictional losses and wear.

Superconducting Magnetic Levitation



Passive stable levitation, but stiffness is low

Shaped Magnet and HTS Bulks



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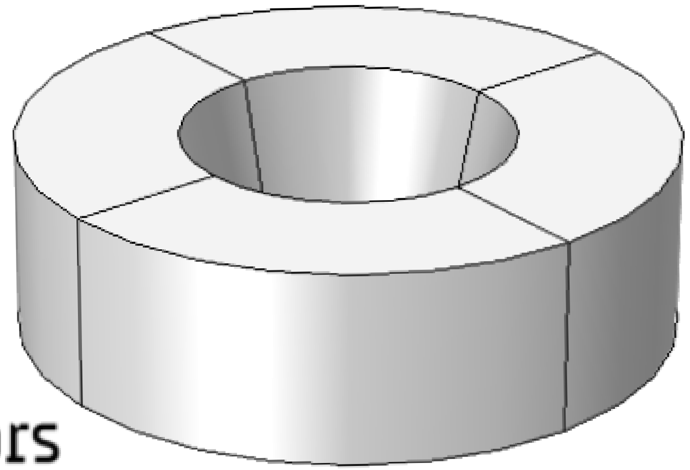
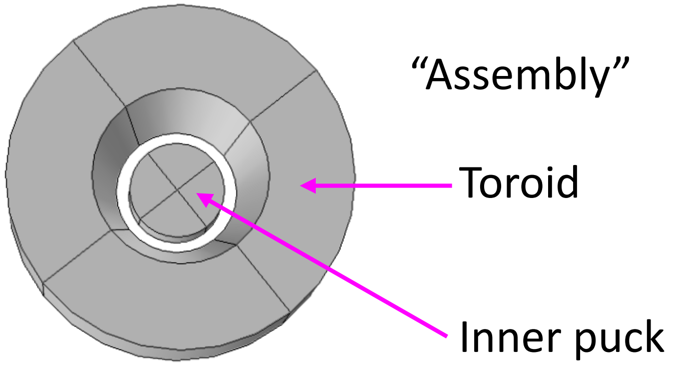
N50 Nd-Fe-B
Conical frustum

Aim:
To produce high stiffness coupled with high levitation force.



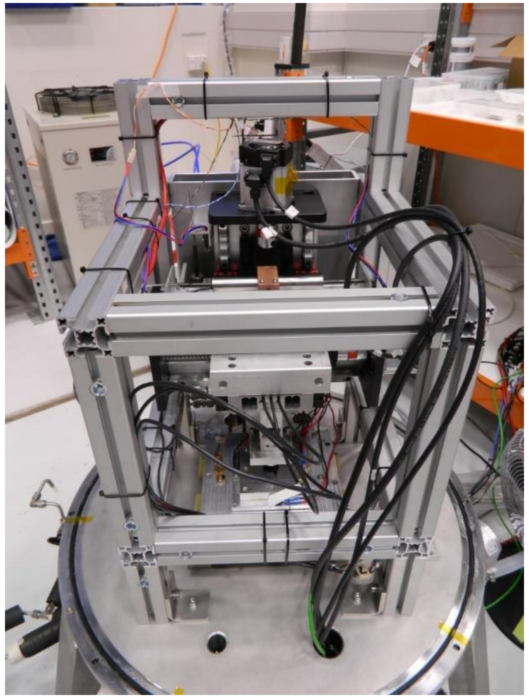


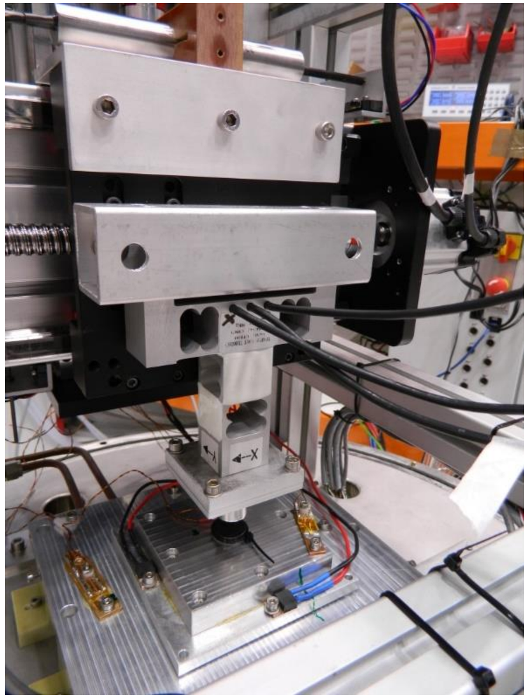
Melt-processed $YBa_2Cu_3O_{7-d}$

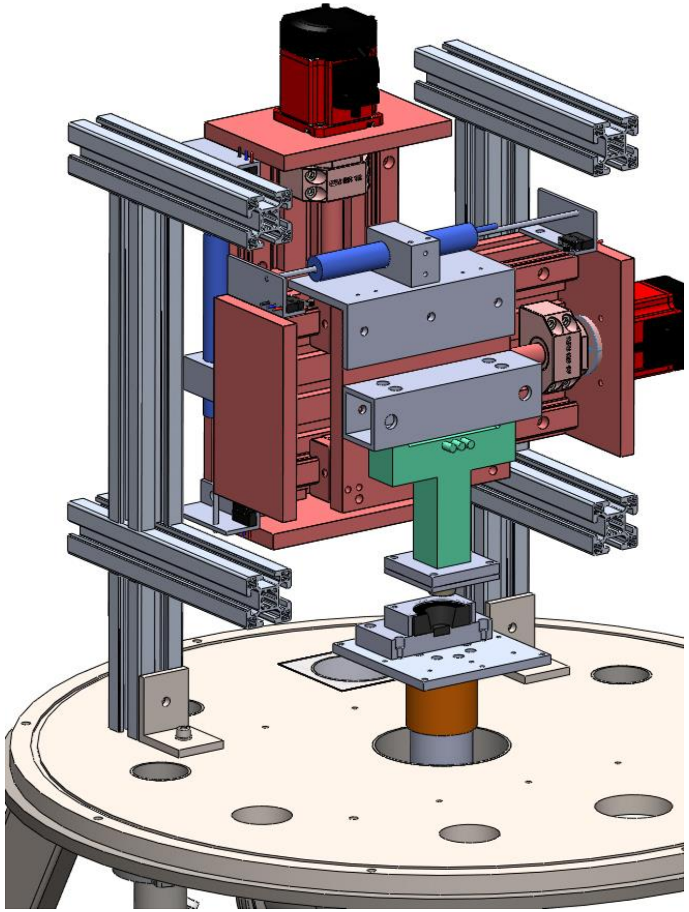
can superconductors

Measurement Test Rig

Cryocooled measurements down to 42 K.
3-axis load cell ±500 N, 10 Hz acquisition rate.
Lateral (x) and vertical (z) displacement system, 0.5 mm/s.







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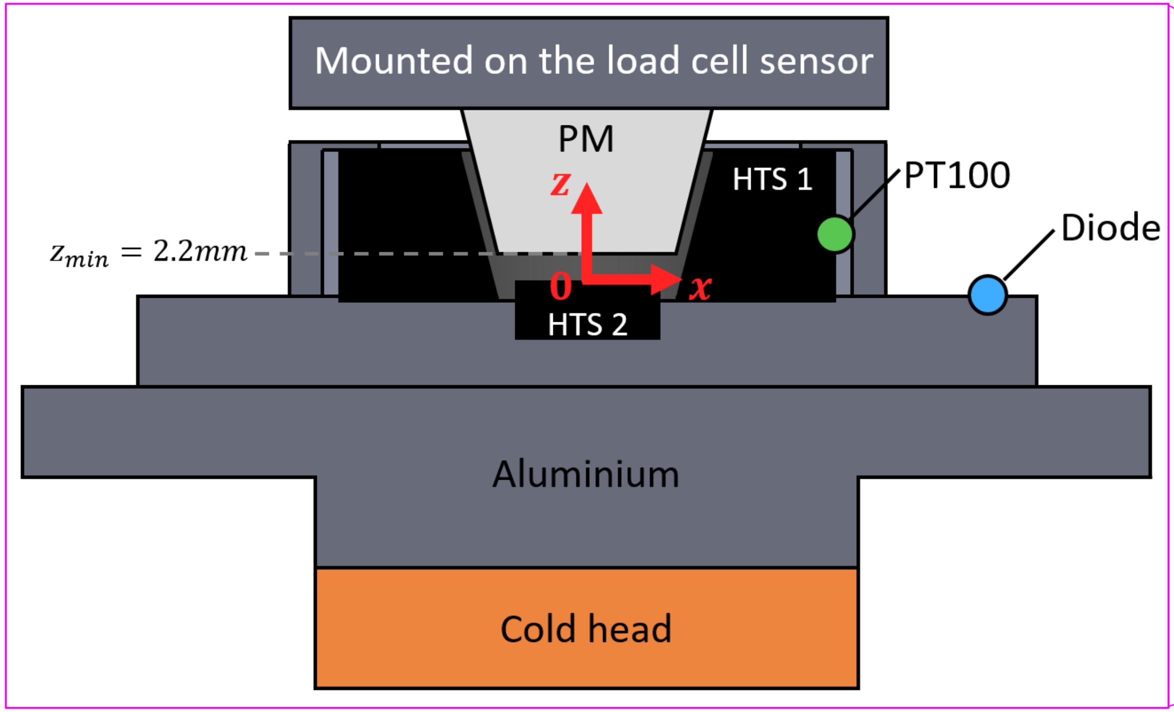
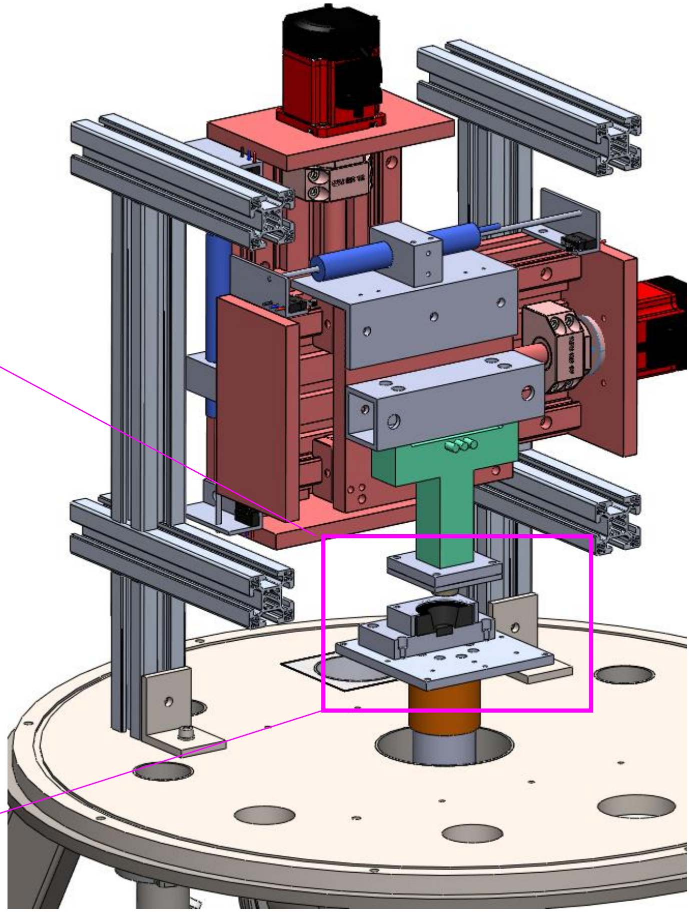




Finite Element Simulation

H-formulation method:
Quéval et al., Supercond. Sci. Technol. 31, 084001 (2018)

COMSOL

Non-linear resistivity

$$\rho_{SC}(\mathbf{J}) = \frac{E_c}{J_c}\left|\frac{\mathbf{J}}{J_c}\right|^{n-1}$$

J: current density

J_c: critical current density at $E_c = 10^{-4}$ V/m

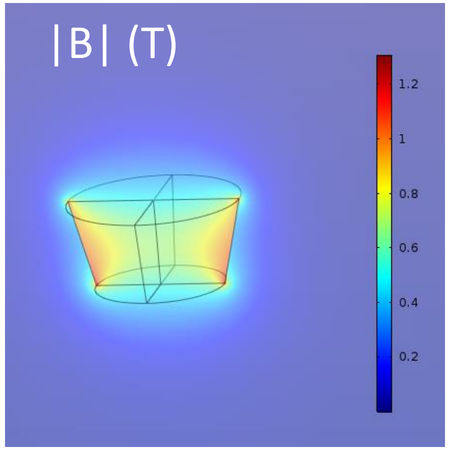
n: 21

Speed: 1 mm/s

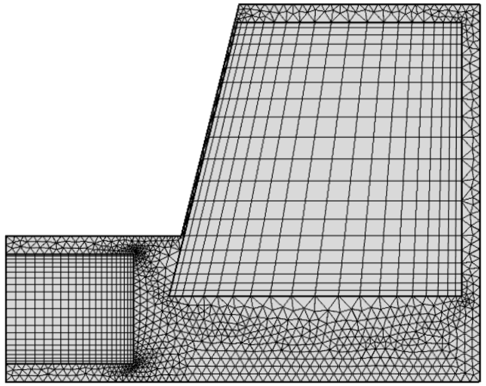
Forces

$$\mathbf{F} = \int_{\mathrm{HTS}} (\mathbf{J} \times \mathbf{B})\, dV$$

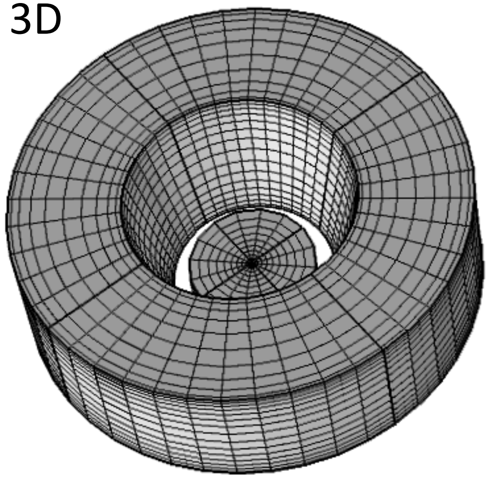
PM field (*A*-formulation) applied as boundary condition



2D Axisymmetric

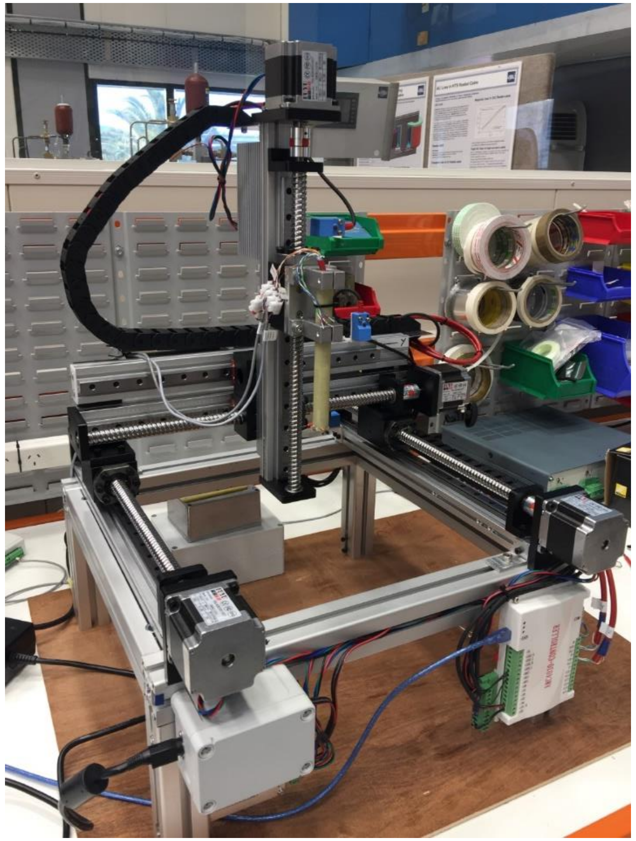


3D

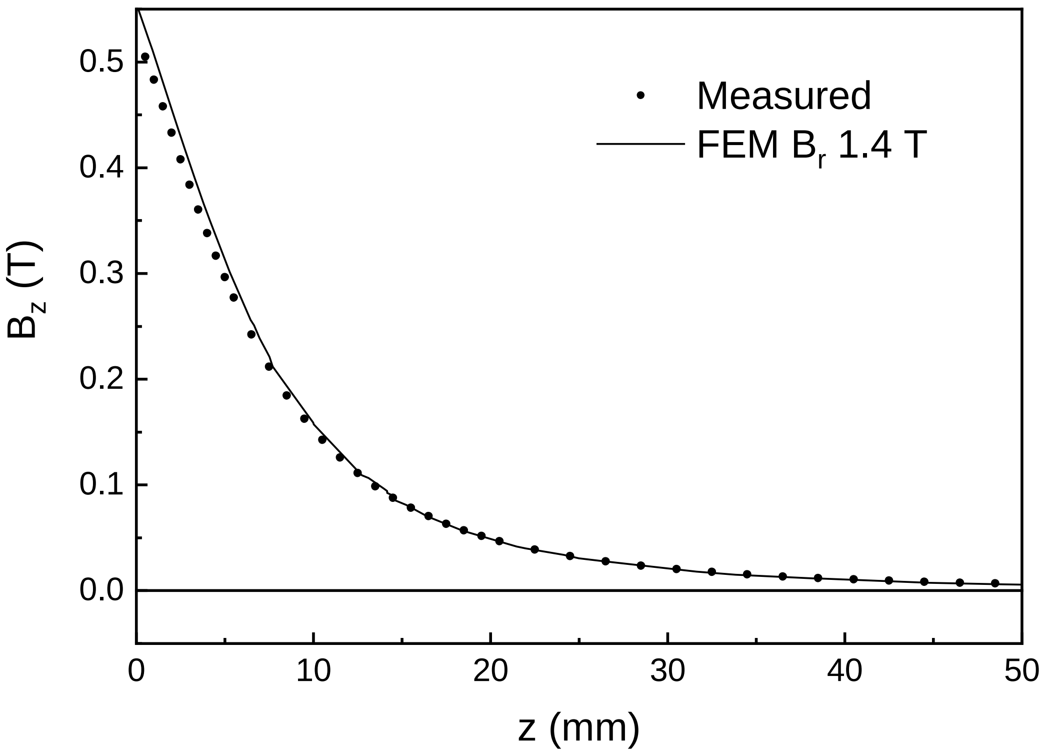


Magnet Mapper

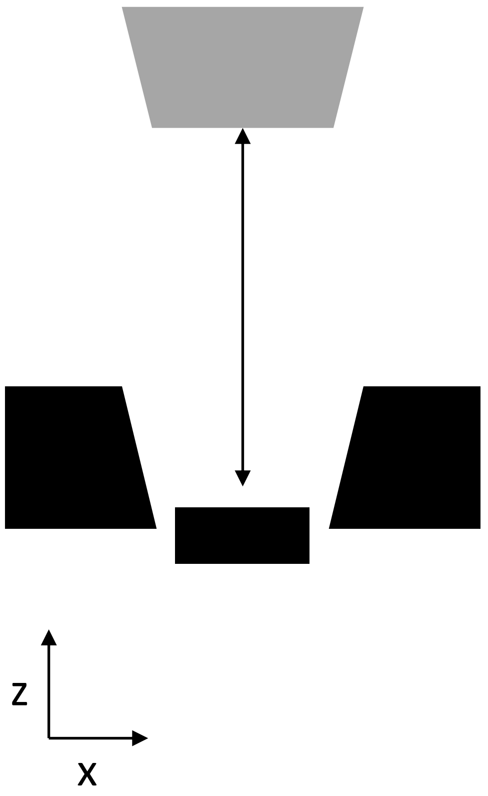
3-axis B_z scanner

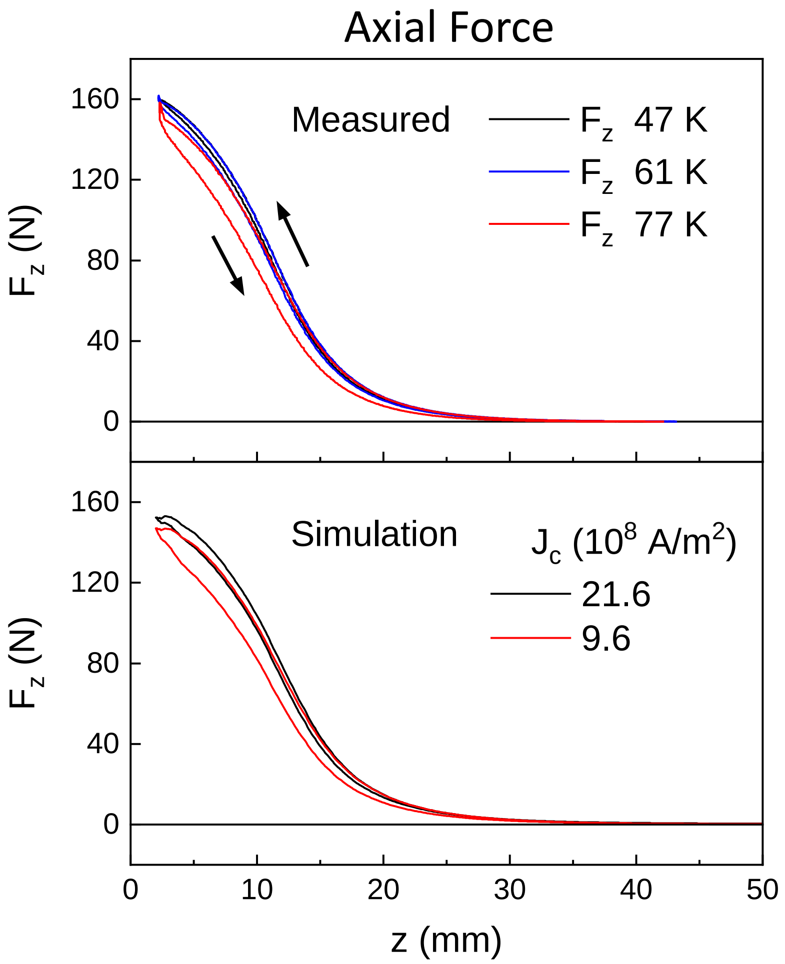


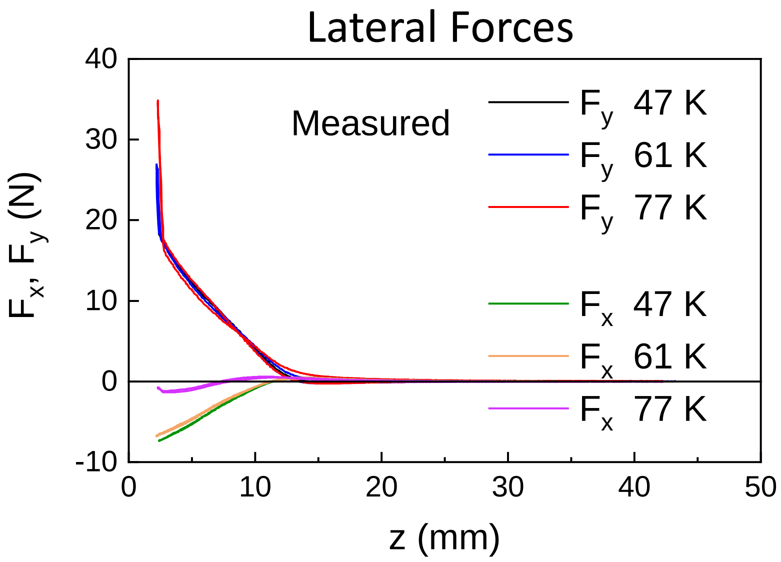
Verified magnet field strength



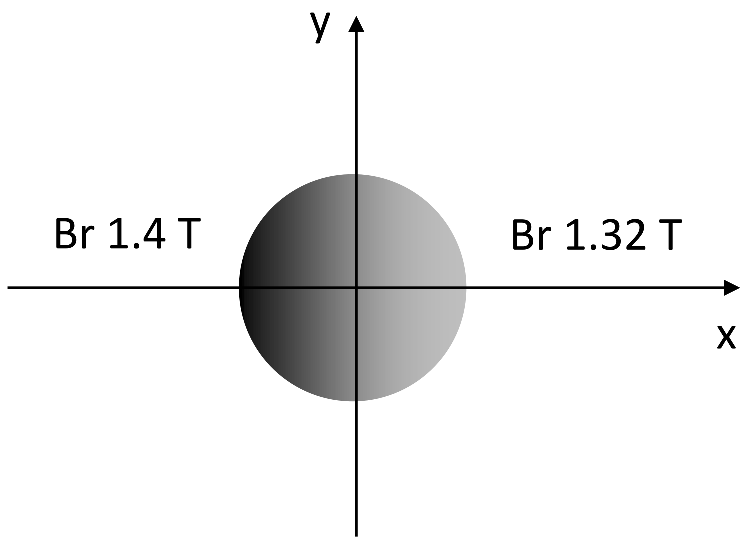
Zero Field Cooled Axial Displacement



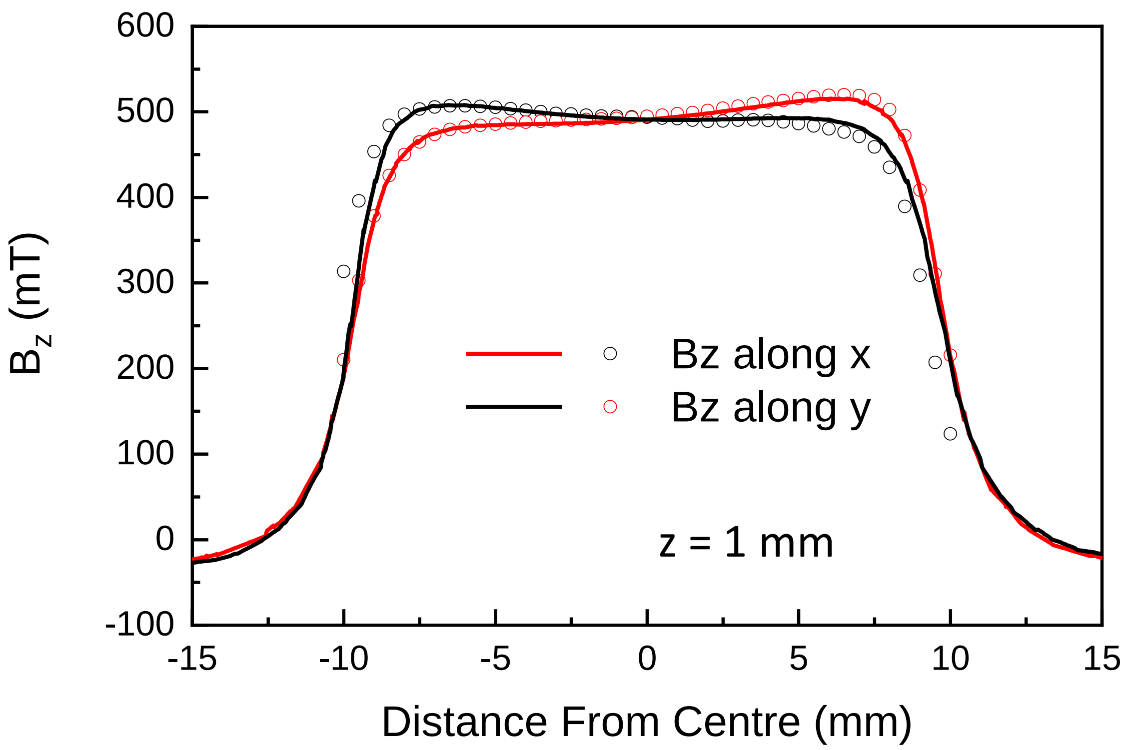




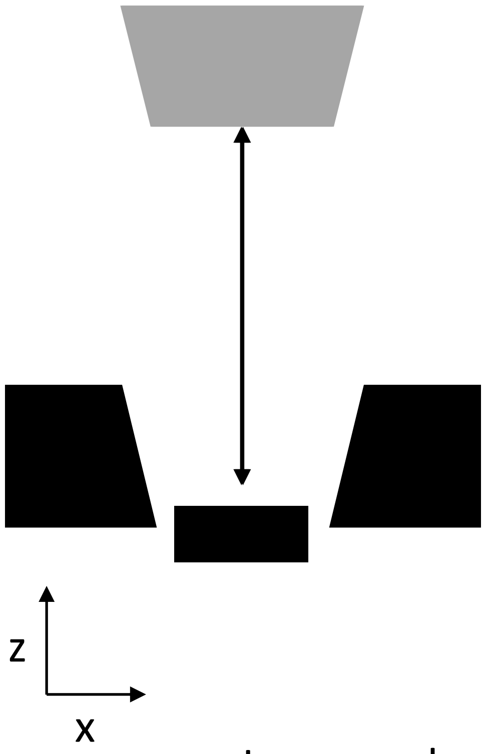
Magnet Alignment & Homogeneity

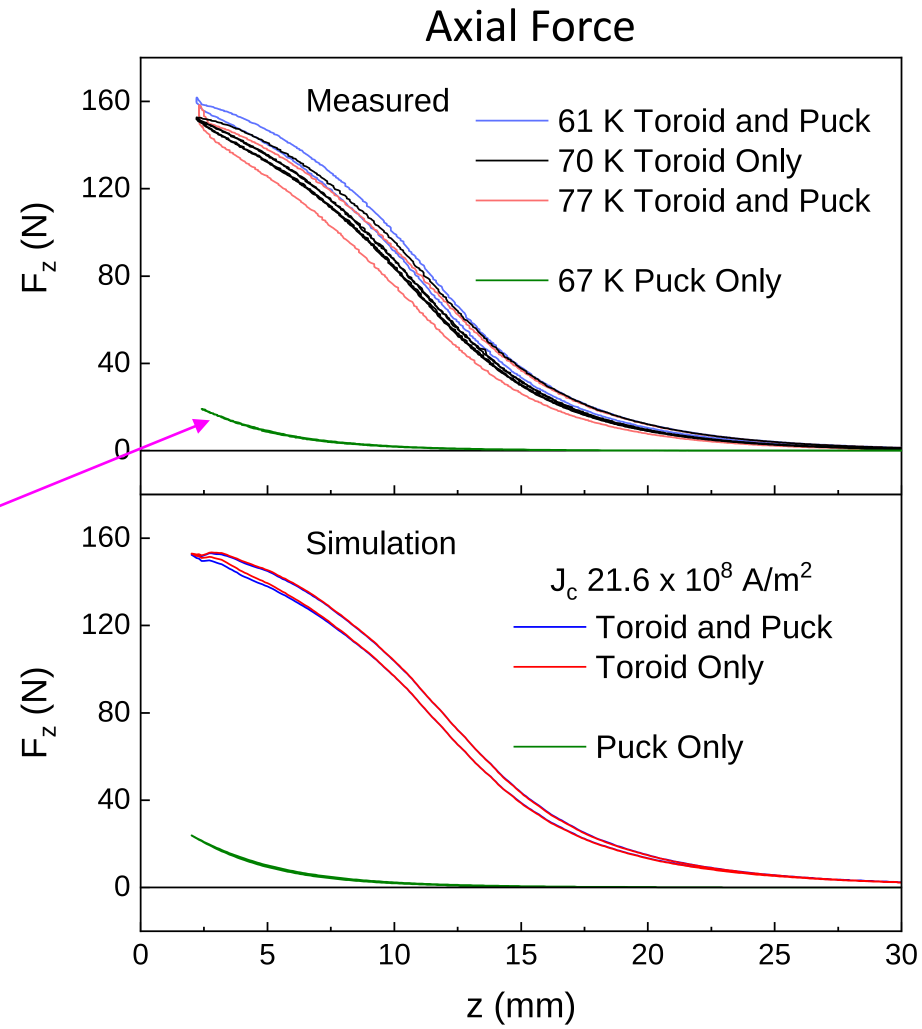


6% variation in Br along x and -1 degree tilt along y



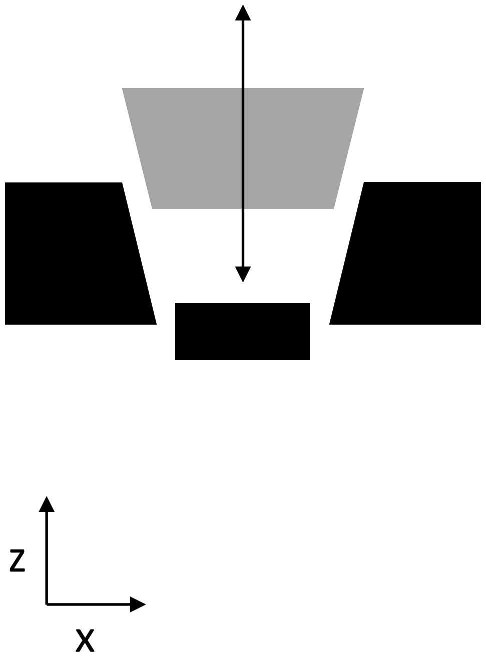
Non Additive Force Contributions

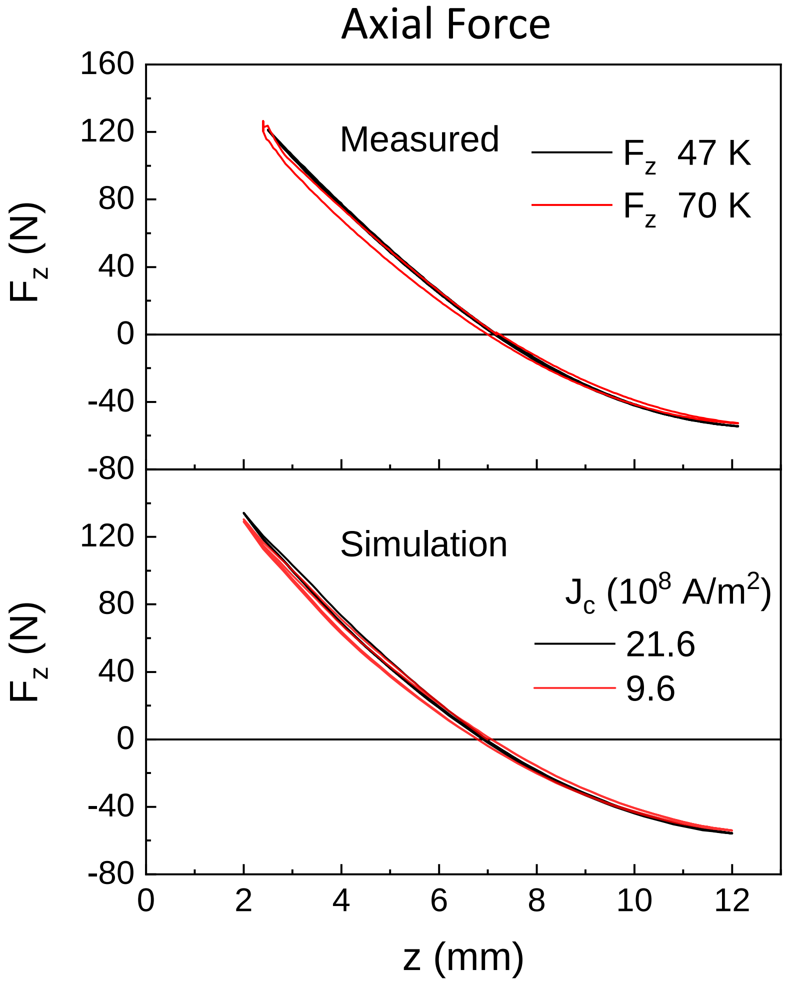


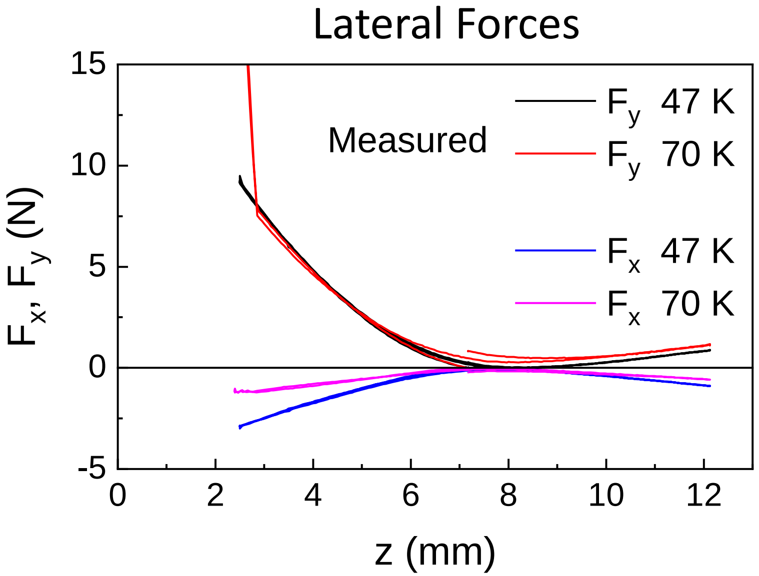


Inner puck makes no contribution to the assembly

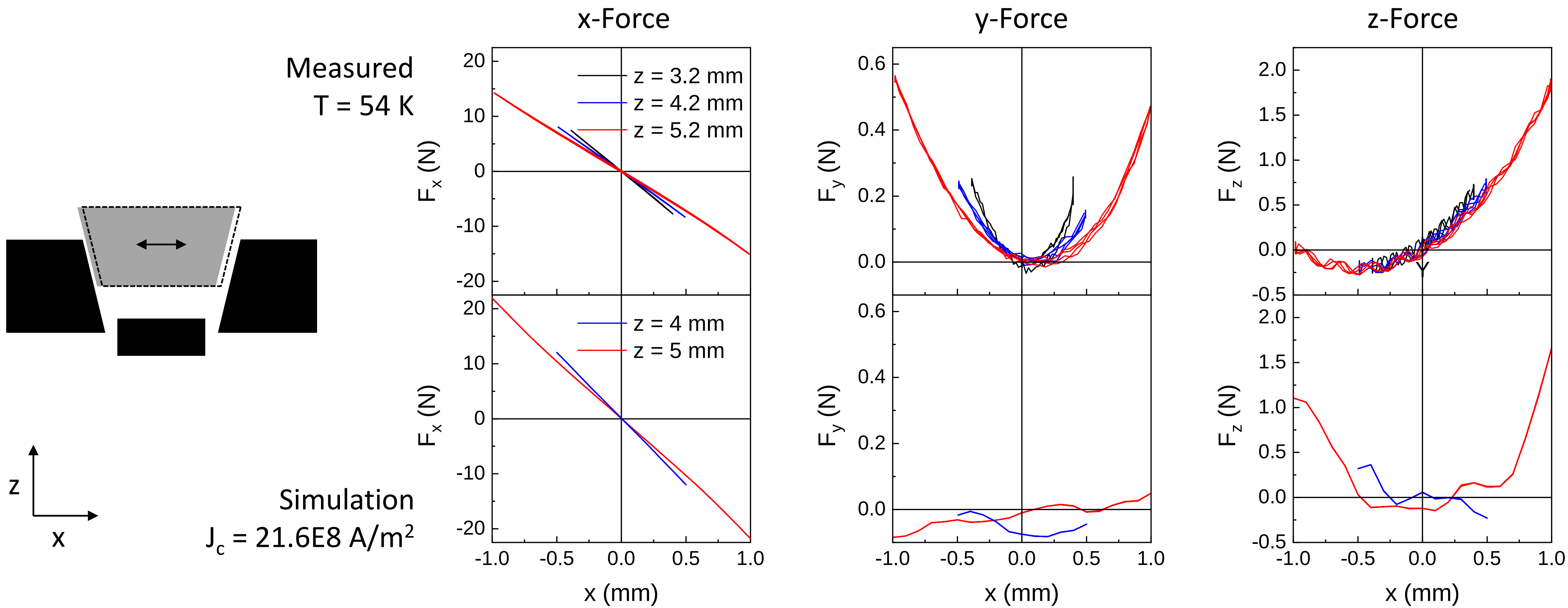
Field Cooled Axial Displacement



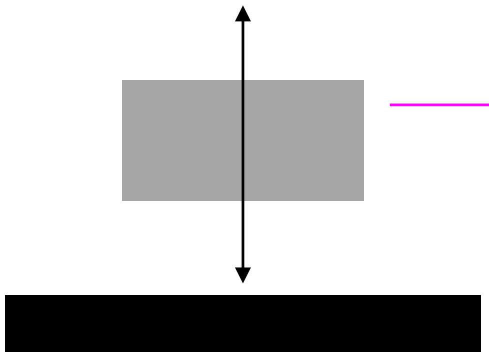




Field Cooled Lateral Displacement

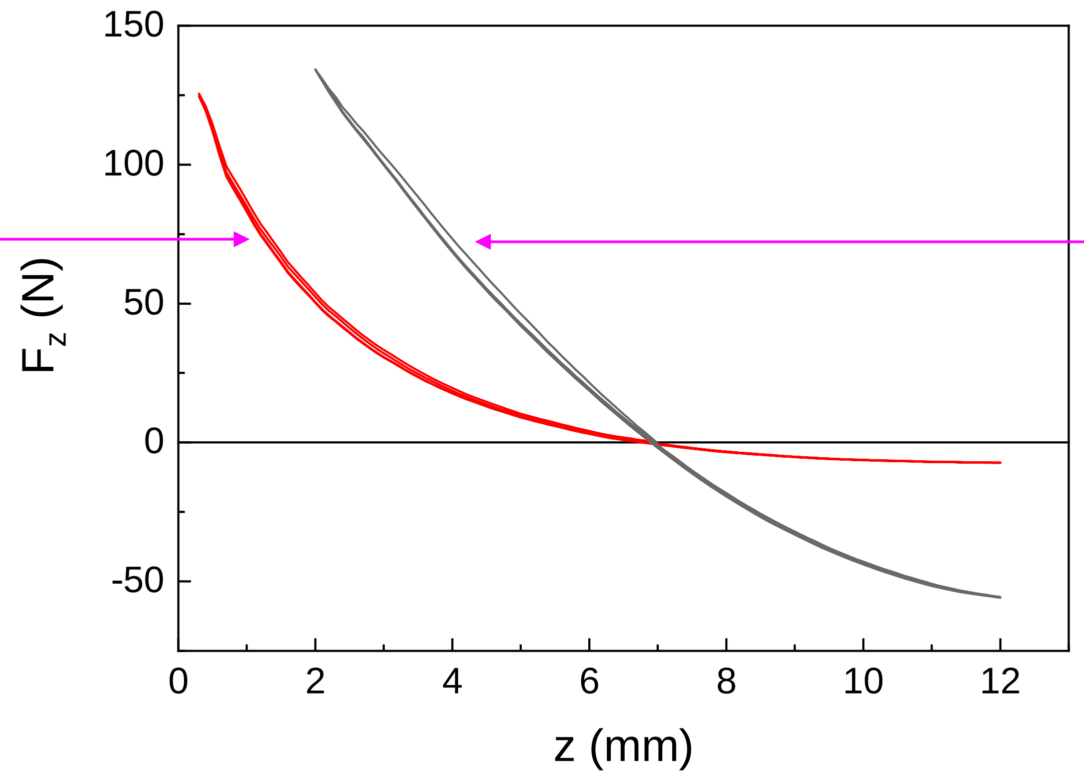


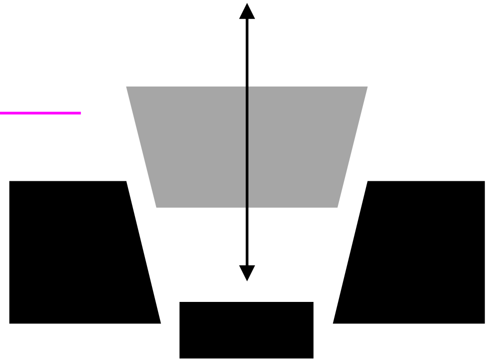
Performance Advantages



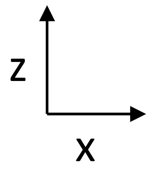
50 mm diameter HTS
25.4 mm diameter PM

Simulated z-Force: Field-Cooled Axial Displacement

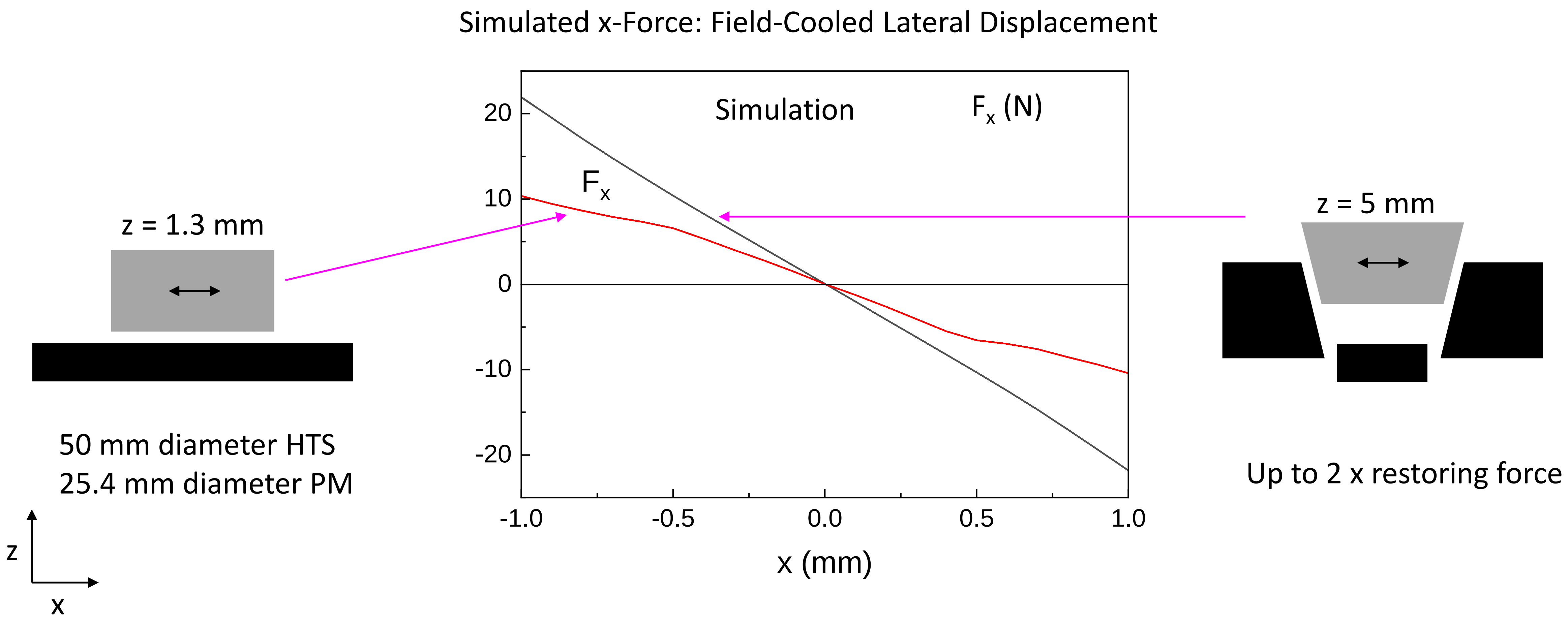




Higher restoring force
More consistent stiffness

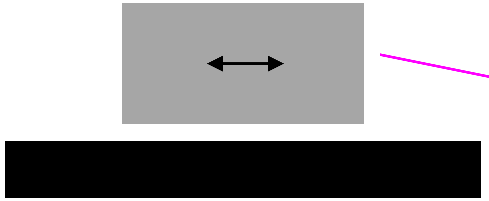


Performance Advantages



Performance Advantages

z = 1.3 mm



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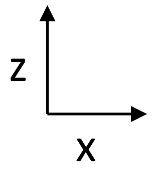
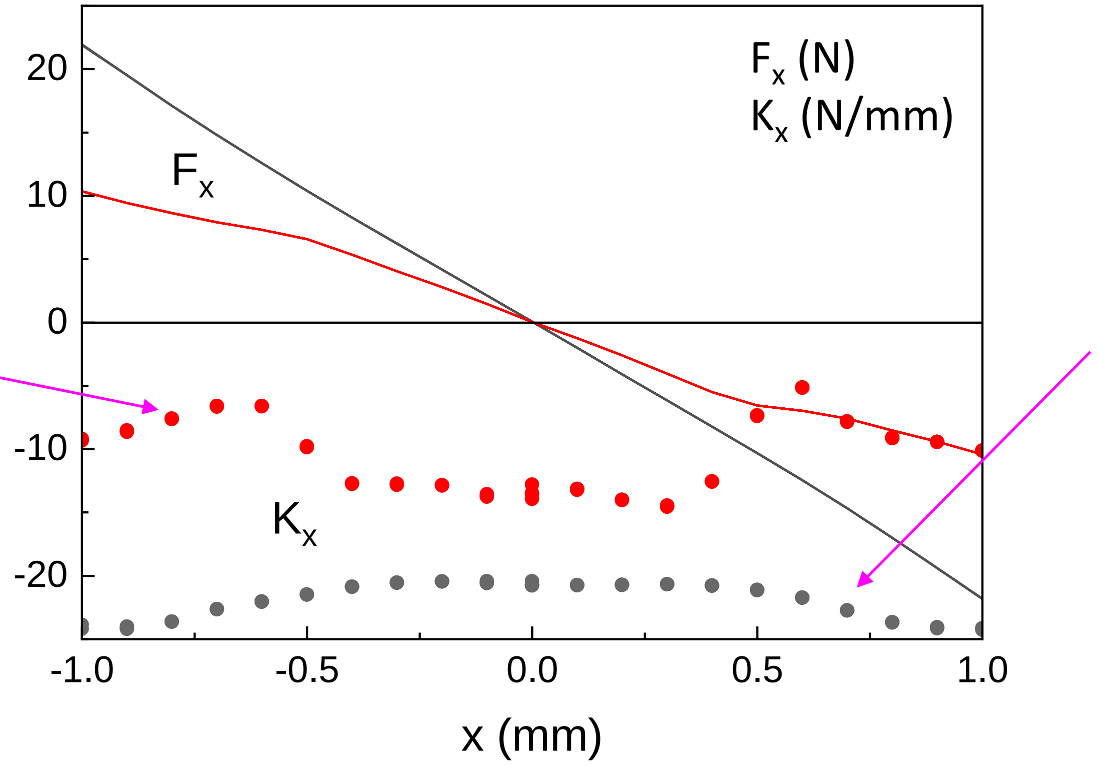
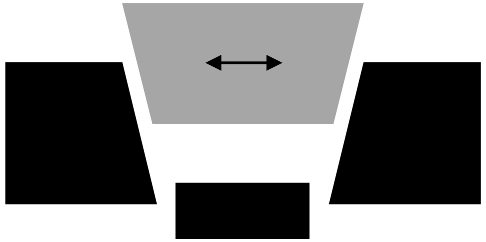


Simulated x-Force: Field-Cooled Lateral Displacement



z = 5 mm



Up to 2 x restoring force
Up to 4 x stiffness

Summary

- For axial displacements, the assembly produces higher and more consistent stiffness, as well as stronger restoring forces.
- For lateral displacements, the assembly produces up to double the lateral force and up to four times the stiffness.
- The small inner puck contributes negligible force to the assembly and can be eliminated from the bearing design.
- Next step: high-speed (25000 RPM) dynamic studies

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