Modeling and Testing of an Improved HEMM Linear Motor

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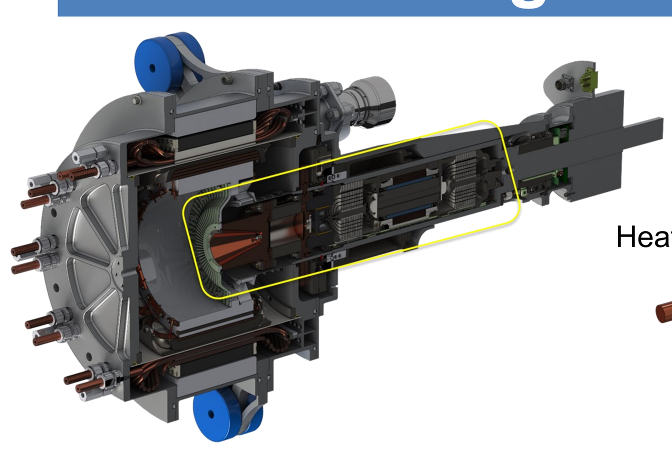
Problem Statement

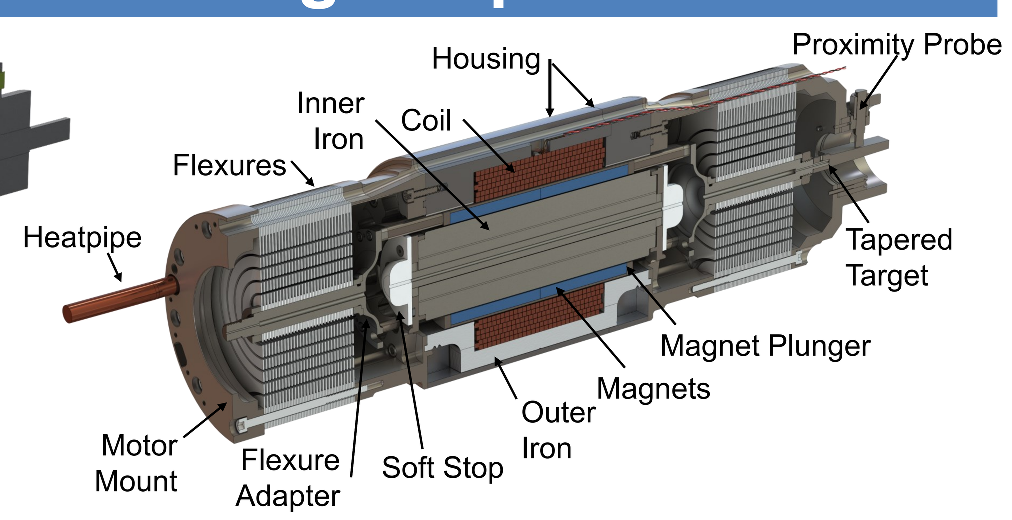
Electrified aircraft propulsion systems require lightweight and highly efficient powertrain components including motors. Superconducting rotor coils can help enable such high-performance motors, but keeping the superconductors at the required cryogenic temperature is a challenge. NASA's 1.4 MW High Efficiency Megawatt Motor (HEMM) solves that problem by integrating a rotating pulse-tube cryocooler into the shaft. The cryocooler acoustic section is driven by a linear motor. This paper reports modeling, building, and testing a second version of that motor. Results reported here show significant improvements over the first version but also reveal remaining deficiencies.

Linear Motor Key Requirements			
Outer diameter	≤100 mm	Peak output force	700 N
Output movement range	±13 mm	Operating frequency	56 Hz

Electromagnetic Design Improvements



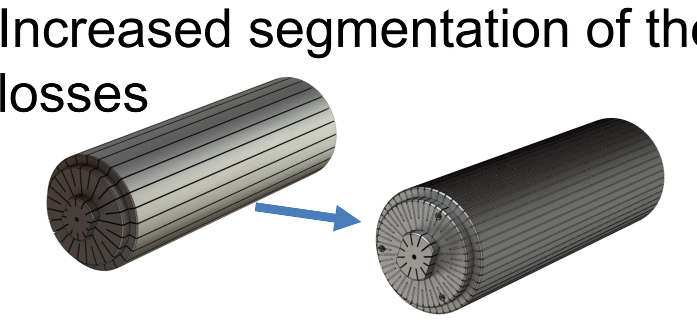
High Efficiency Megawatt Motor (HEMM) cross-section



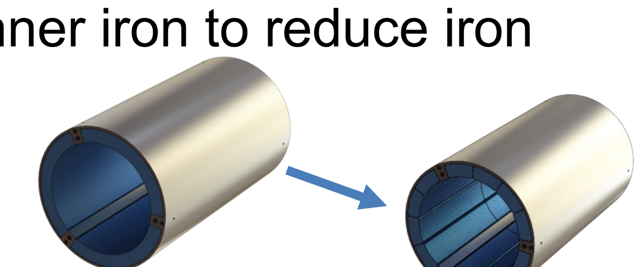
Linear motor cross-section

The V1 linear motor had several electromagnetic design issues that were improved for the V2 motor:

- Increased thickness of outer iron to reduce saturation
- Increased segmentation of the inner iron to reduce iron losses

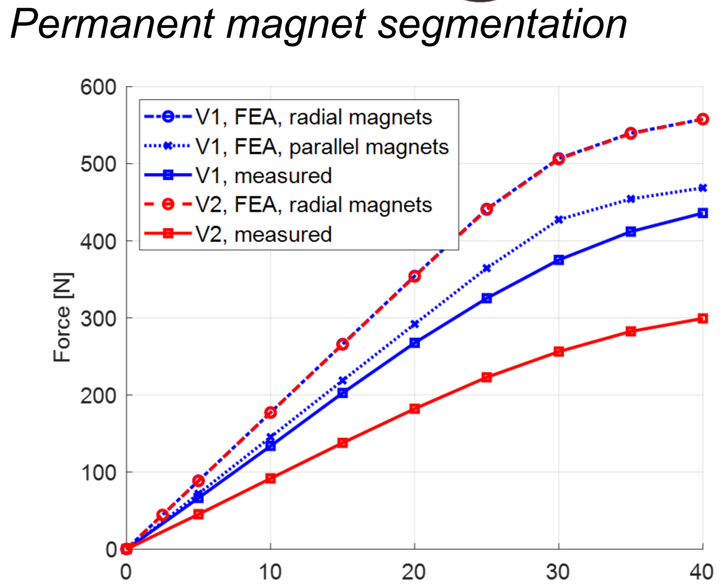


Inner iron showing radial slice segmentation



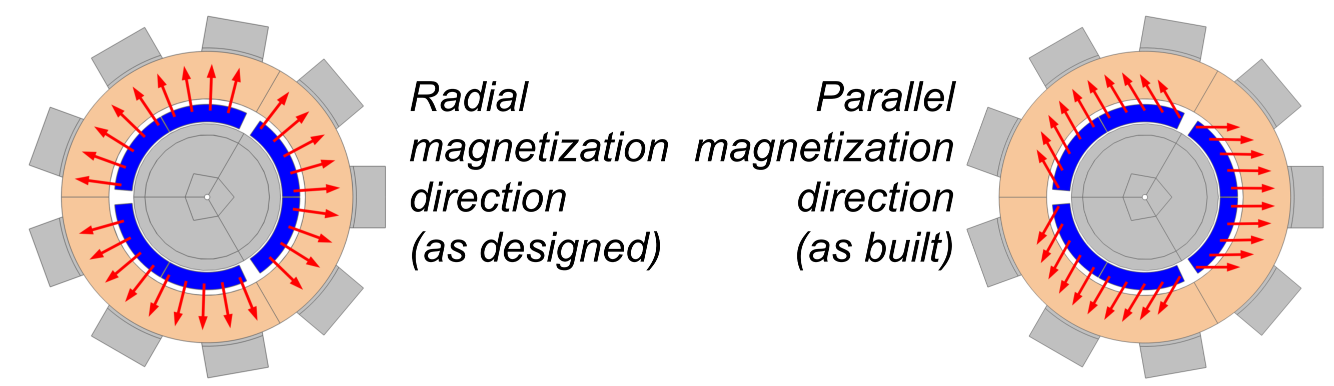
Permanent magnet segmentation

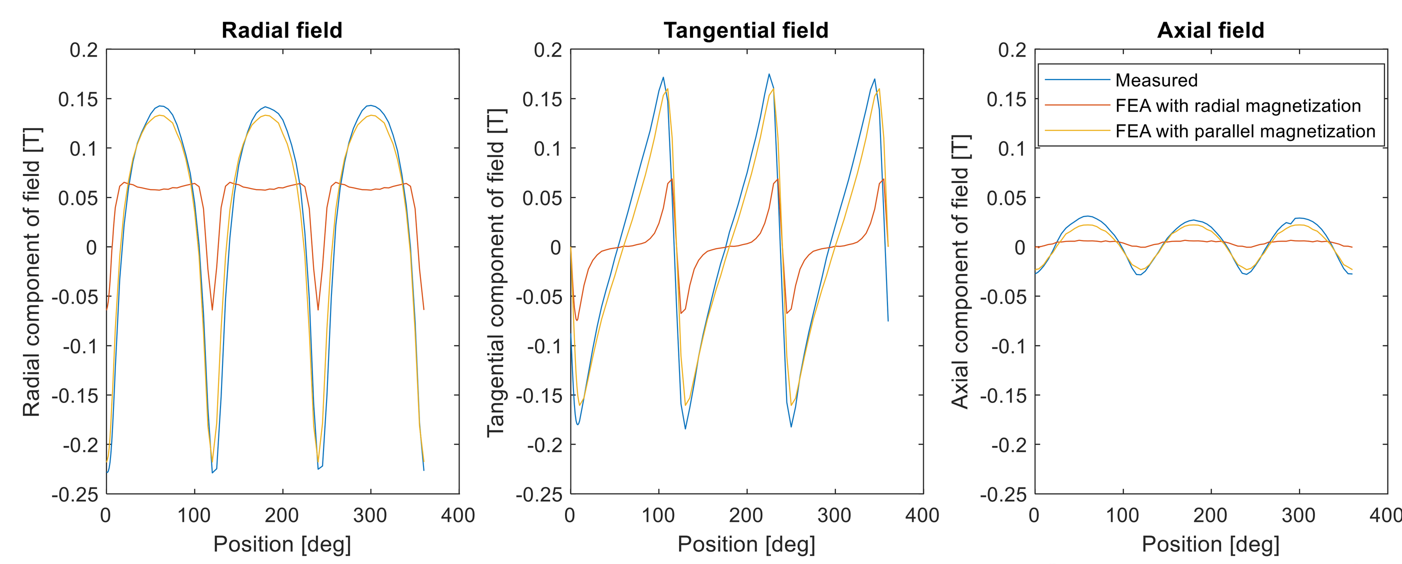
- Increased segmentation of the permanent magnets to reduce eddy current losses
- Increased permanent magnet grade to offset reduced magnet volume due to gaps between segments



Force vs current at center position for various magnet configurations

Impact of Magnetization Direction

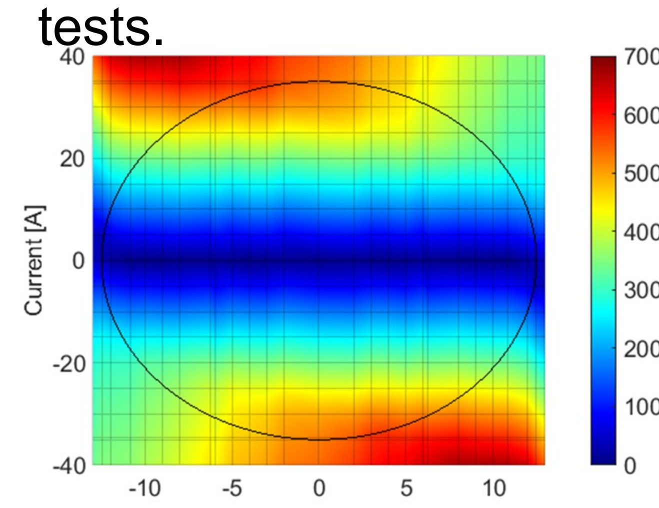




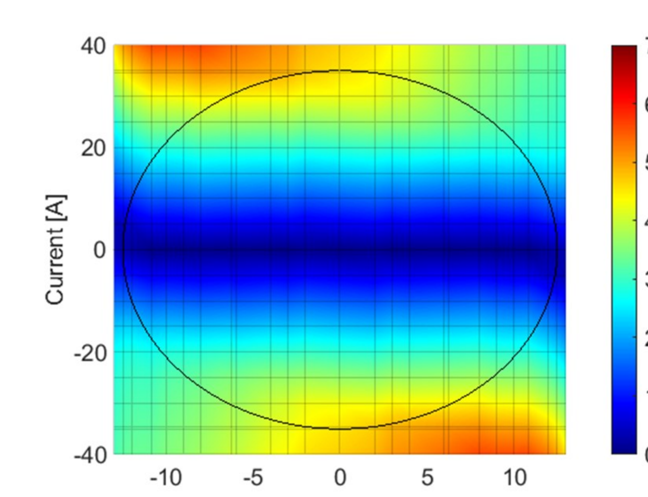
In the center position, the measured output force was 46% lower than modelled in FEA. Measuring the magnetic field generated by the magnet plunger in air revealed two issues:

1. Each magnet segment was magnetized along a single axis rather than radially
2. The magnets were not fully magnetized, indicating that insufficient field was applied during magnetization or that demagnetization occurred at some point

The original, V1, plunger was nearly fully magnetized but also magnetized along a single axis rather than radially. With the V1 plunger installed, measured force was about 11% below the force modelled with parallel magnetization and 26 % below the original design target. The V1 plunger was used for all future tests.



With V2 plunger and radial magnetization



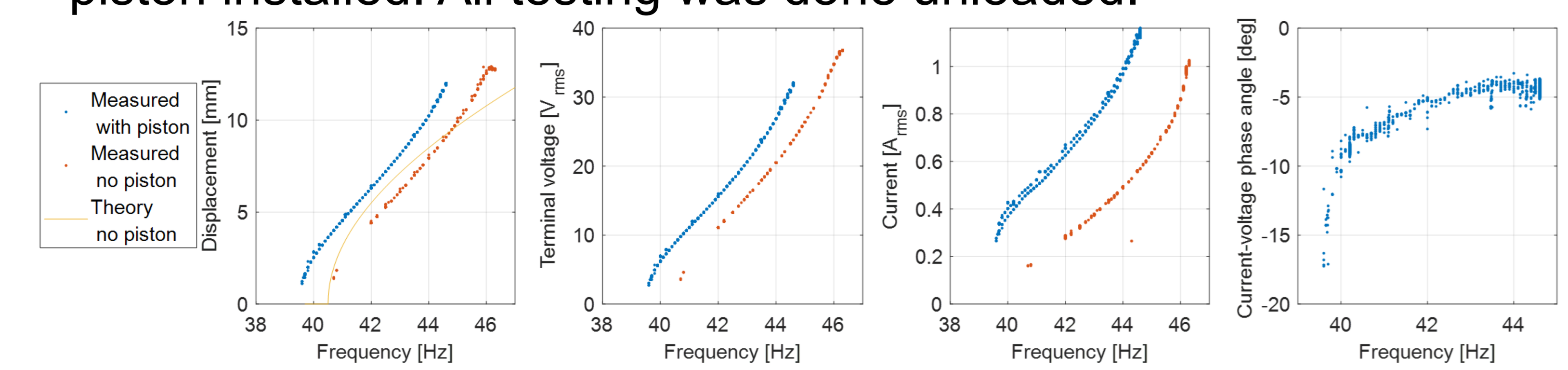
With V1 plunger and parallel magnetization

Colormaps of modeled force magnitude vs current and position. The black circles indicate operating points used during resonant operation.

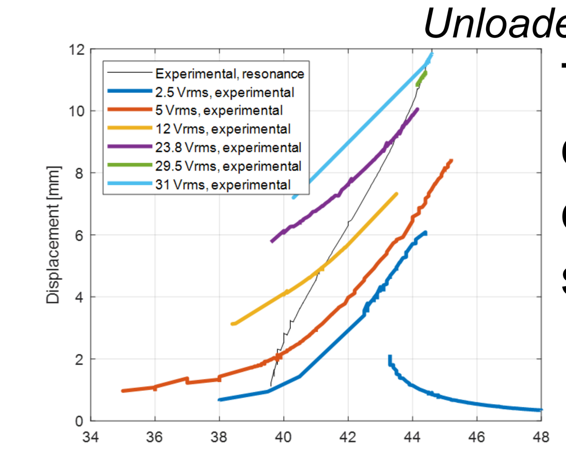
FEA modeling of the motor shows significantly degraded output force due to iron saturation made worse by parallel magnetization, particularly for displacements greater than 11 mm.

Dynamic Operation Results

We successfully operated at resonance (defined as force and velocity being in phase) over a range of frequencies and displacements. Testing was repeated with and without the piston installed. All testing was done unloaded.

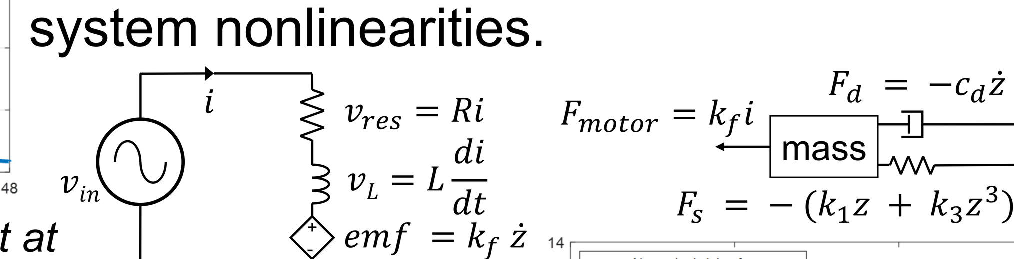


Unloaded motor performance at resonance.



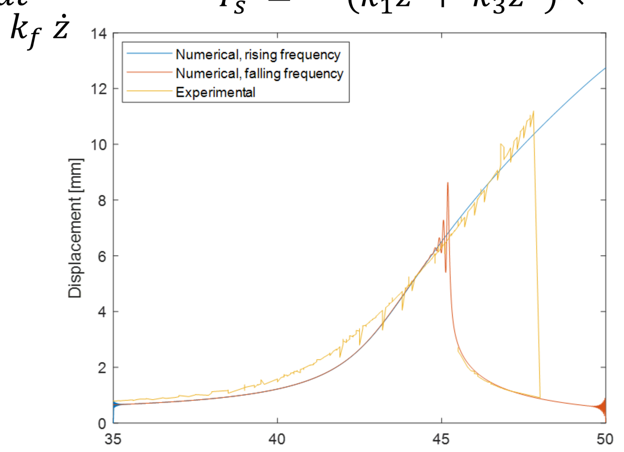
Unloaded motor displacement at various voltages and frequencies.

The resonant frequency changes depending on the displacement magnitude due to nonlinear flexure stiffness and other system nonlinearities.



Numerical modeling showed:

- Performance is very sensitive to changes in the spring constant and mass
- Cubic stiffness and a simplified nonlinear back-emf constant do not fully explain nonlinear characteristics



Displacement vs frequency with 5 V_{rms} from numerical model and experimental results.

Conclusion

The V2 linear motor for the HEMM cryocooler performed significantly better than the V1 motor despite some setbacks along the way.

- More detailed FEA modeling guided design changes to reduce losses and improve performance.
- Magnetic field measurements revealed that the magnets had parallel magnetization rather than radial, resulting in degraded performance.
- Dynamic testing showed controllable resonant and off-resonant operation.
- Numerical modeling of the motor showed that cubic stiffness alone does not explain the nonlinear resonant behavior of the system.

References:

K. P. Duffy, P. J. Passe, R. W. Dyson, R. H. Jansen, Y. D. Jesus-Arce and A. D. Anderson, "Design, Analysis, and Testing of the HEMM Cryocooler Linear Motor," in *2020 AIAA/IEEE Electric Aircraft Technologies Symposium (EATS)*, New Orleans, LA, USA, 2020.

R. W. Dyson, R. H. Jansen, K. P. Duffy and P. J. Passe, "High Efficiency Megawatt Machine Rotating Cryocooler Conceptual Design," in AIAA Propulsion and Energy Forum, Indianapolis, IN, USA, 2019.

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