# Conclusions of a Cryogenic Motor Configuration Study for Aircraft Propulsion

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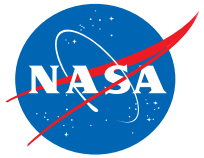


# Agenda

- Motivation
- Motor specifications
- Motor design codes
- Motor optimization results
  - Permanent magnet rotors
  - Superconducting rotors
- Comparison of 2 motor configuration finalists
- Conclusions

# Motivation

Enable more fuel-efficient air transportation and advanced engine cycles
via electrified propulsion systems

- **Economic benefits:** reduced fuel consumption · decreased energy costs & increased cost stability · maintain U.S. competitiveness · reinvigorate existing aircraft markets & strengthen emerging markets
  - *Example*: for 10 year operation of a specific aircraft, 1% fuel consumption is worth $3M
  - *Example*: ~50% of a twin-aisle aircraft's weight is fuel (at max take-off condition)
- **Societal benefits:** global access to air travel can continue to grow
- **Environmental benefits:** reduced impact on climate · improved air quality
  - Insufficient to only focus on $CO_2$ emissions and sustainable aviation fuels
- To achieve significant impact, focused on single- and twin-aisle aircraft (~150+ passengers)
  - Aircraft-level studies demonstrate that higher power electrified propulsion systems enable larger reductions in energy consumption (fuel cost) [1-3]


1. https://ntrs.nasa.gov/api/citations/20210016661/downloads/TM-20210016661.pdf
2. https://doi.org/10.2514/6.2024-1326
3. https://ntrs.nasa.gov/api/citations/20240001480/downloads/NASA-TM-20240001480.pdf

# Specifications of 'Vision' Motor

| Parameter | Goal | Stretch Goal |
|---|---|---|
| Continuous power, MW | 5 | - |
| Rated speed, rpm | 1,500 – 3,000 | - |
| Efficiency at rated speed | ≥ 99.5% | ≥ 99.8% |
| Continuous specific power, kW/kg | ≥ 20 | ≥ 30 |
| DC bus voltage (relative to neutral), V | ≥ ±270 | ≤ ±1,000 |
| Rated voltage of insulation, V | ≥ 1,000 | 2,000 |
| Equivalent tip speed at outer radius, m/s | ≤ 100 | - |

- Motor for directly driving propeller / fan
- Considering fully cryogenic (superconducting (SC) rotor) & partially cryogenic (permanent magnet rotor)
- Considering either SC, high purity aluminum, or Cu Litz as stator conductor
- Technology Readiness Level (TRL) advancement prioritized over performance
- Upper limit of ±1,000 V to limit material development & electronics packaging issues

# Rationale for Efficiency Specs

- Most of a motor's power loss is in its stator → high efficiency is necessary to ensure (a) cryocooling system has manageable size and (b) achieving small temperature gradient in stator is feasible
- Be compatible with future $H_2$ burning engines, which will set max quantity & flow rate of liquid hydrogen (LH2) on aircraft
- Limit penalty of operating cryogenic

Performance & specs of future LH2-burning engine

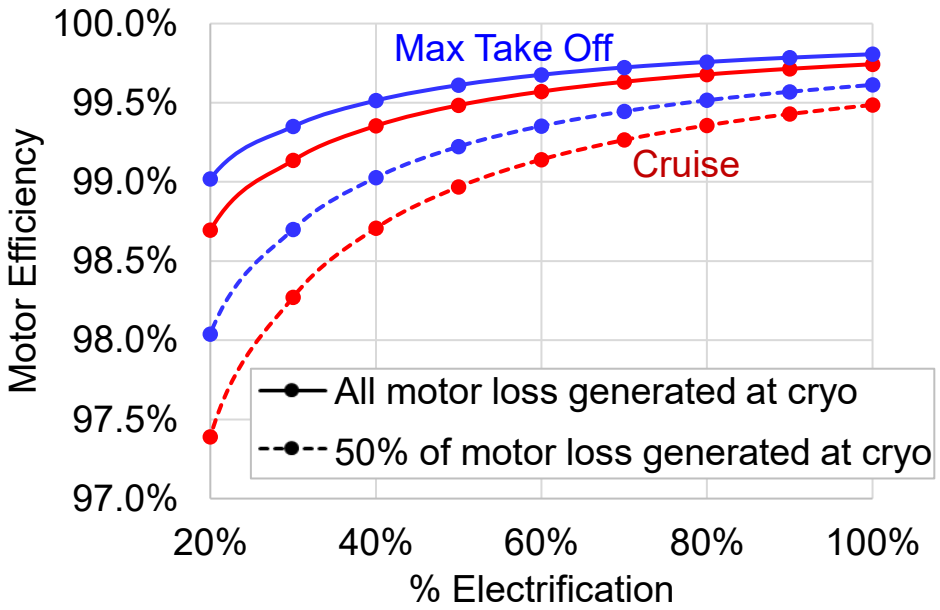
✚

Assume turboelectric powertrain with same efficiency for each component

Generator → AC/DC → DC cable (lossless) → DC/AC → motor

⇨

Req'd motor efficiency to avoid extra cryocooling in LH2-burning aircraft




**Takeaway**

Future LH2-burning aircraft with modest to high electrification will require that cryogenic electric machines have an efficiency approaching or greater than 99.5%

# Motor Design Choices

**There are 3 main choices to make:**

1. What motor configuration? (What does it look like?)
   - Focus of this talk

2. What cryogenic coolant? (and temperature)
   - Liquid nitrogen
   - Liquid neon
   - Liquid hydrogen
   - **Gaseous helium**

3. What conductor to use in stator?
   - conventional, fine diameter
     - **Cu Litz** — All other configurations
     - Al Litz
   - high purity metal
     - ≥ 99.999% Al (HPAL)
   - superconductors
     - **REBCO** — Helmholtz configuration
     - MgB2
     - Bi-2212

# Hierarchy of motor configurations studied

Configuration

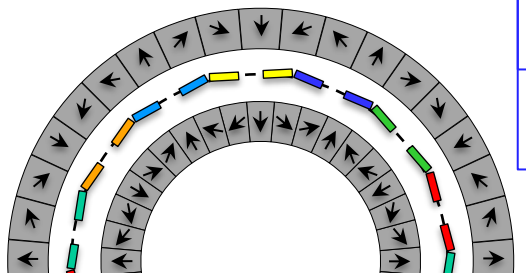
**Stator type**

**Rotor type (motor type)**

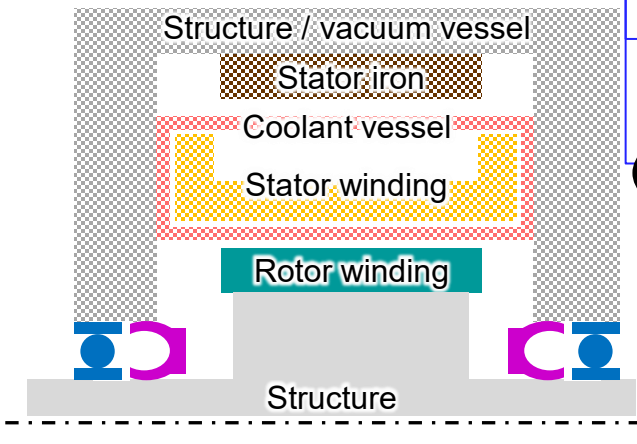
**Magnetic flux direction**

**Construction**

**Sub-configuration choices**



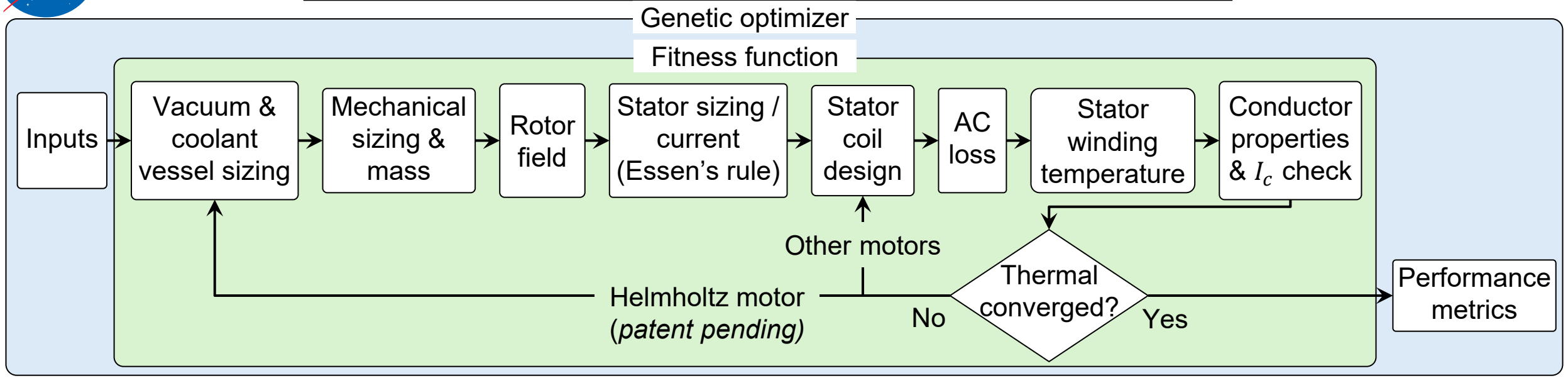
- Cryogenic stator
  - Permanent magnet rotor (partially cryo)
    - Radial flux
      - 1. Stator is vacuum vessel
      - 2. Rotor is vacuum vessel
      - ~~3. Rotor-stator-rotor, concentrated~~
      - ~~4. Rotor-stator-rotor, distributed~~
      - 5. Helmholtz
        - Coolant A
          - Stator conductor A
        - ...
    - Axial flux
      - 6. Rotor – stator – rotor, stator is vacuum vessel
      - ~~7. Rotor – stator – rotor, rotor is vacuum vessel~~
    - Radial + axial flux
      - 8. 3-rotor, no iron
      - ~~9. 3-rotor, with iron~~
  - Superconducting rotor (fully cryo)
    - Radial flux
      - ~~10. Outer rotor~~
      - ~~11. Rotor-stator-rotor~~
      - ~~12. Stator-rotor-stator~~
      - 13. Inner rotor
        - Coolant A
          - Stator conductor A
        - ...
    - Axial flux
      - ~~14. Rotor – stator – rotor, zig-zag~~
      - ~~15. Rotor – stator – rotor, concentrated~~
      - 16. Stator – rotor – stator, distributed
      - 17. Stator – rotor – stator, concentrated




**Takeaway**

Down selected to 8 configurations (5 PM rotor, 3 SC rotor) based on the team's qualitative assessment of 9 factors (size, losses, magnetics, thermal management, structural complexity, rotordynamics)

# Overview of Motor Design Codes




- Analytical equations to calculate rotor & stator magnetic fields over a half period, heat transfer, & AC loss
- Winding surface directly cooled: on one active face (tri-rotor & axial flux) or inner & outer diameters (radial flux)
- Vacuum & coolant vessels sized based on buckling (external pressure) or hoop stress (internal pressure)
- Shafts & bearings sized to direct drive propeller subjected to aircraft maneuvers with ≥90% bearing reliability
- For superconducting rotors:
  - Rotating cryocooler used with Carnot efficiency from [4] & mass based on commercial Stirling coolers [5]
  - Heat load = radiation + 10 W


4. D. Ladner, "Performance and Mass vs. Operating Temperature for Pulse Tube and Stirling Cryocoolers," in International Cryocooler Conference, 2008.
5. https://www.sunpowerinc.com/products/stirling-cryocoolers/cryotel-cryocoolers.

# Motor Design Codes

| Losses considered | Total mass estimated |
|---|---|
| • *In Litz wires*: AC resistive & proximity eddy current losses<br>• *In superconductors*: hysteresis, eddy current, coupling, (also transport in HTS)<br>• Bearing<br>• Windage (Helmholtz motor only)<br>• Pumping fluid through motor<br>• Cryocooler (fully cryo motors)<br>• Iron (where required)<br>• 1.5 kW for rotary vacuum seals (where required) | • Electromagnetic<br>• Shafts & bearings<br>• Vacuum vessels, fluid containment, fluid, & rotors<br>• Cryocooler & thermal connection to it<br>• 10 kg for miscellaneous components |

- 10% margin on torque
- **Most results: 3,000 rpm**
- **All results: ±1,000 V DC bus, 100 m/s equivalent tip speed**

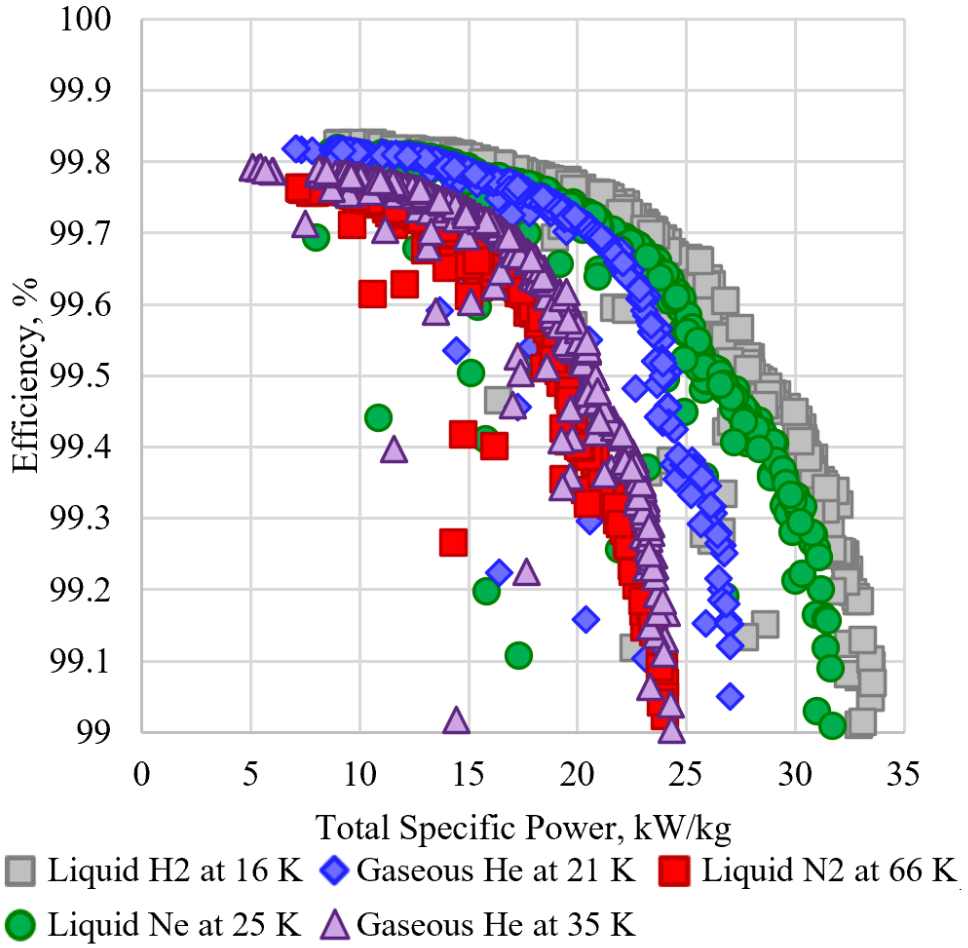
# Comparison of Motor Design Codes to Prior Work

- Motor design codes similar to prior work [6,7]
  - Key revisions:
    - Some refinement and error correction
    - DC bus voltage increased from +/- 270 V to +/- 1 kV
    - Equivalent tip speed increased to 100 m/s
    - Coolant change from LNe to GHe


6. T. F. Tallerico et al., “Cryogenic copper and aluminum Litz wire motors for electric aircraft,” in 2025 IEEE/AIAA Transport. Electrification Conf. and Elec. Aircraft Tech. Symp. (ITEC+EATS), Anaheim, CA, 2025.
7. J. J. Scheidler et al., " Motor configuration trade study for a new technical challenge to develop a 5 MW cryogenic motor and drive," https://ntrs.nasa.gov/citations/20250003104.

# Results – Impact of Stator Coolant

- Considered only radial flux motor with inner HTS rotor and Cu Litz wire stator
- LH2 not considered viable but included for comparison
- Unsurprisingly, liquid cryogens are best at given temperature near upper limit of specific power (where thermal management dominates)
- GHe chosen due to industry interest, much lower density, lack of phase change, and no potential for cavitation issues

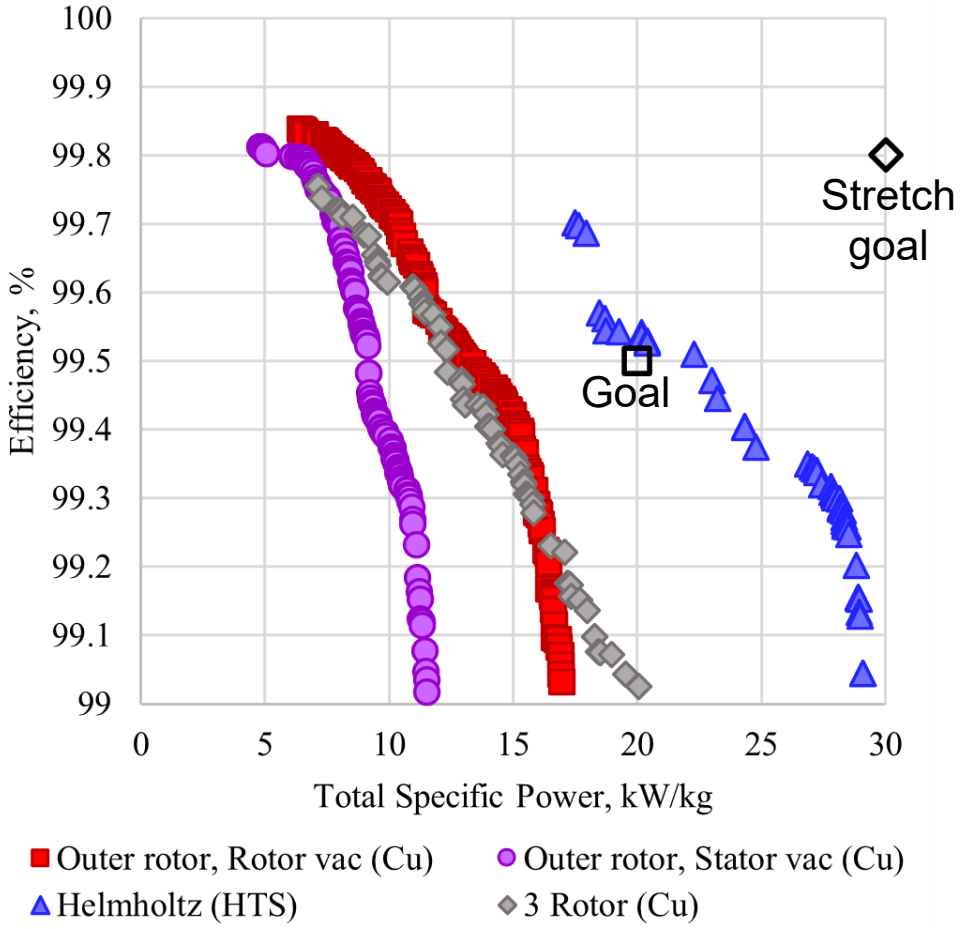



**Takeaway**

Remaining results shown for GHe at 35 K at motor inlet

# Results – Permanent Magnet Rotors

- Axial flux design did not close
  (stator's vacuum & fluid containment vessels too thick [not stiff enough])
- PM motors with Cu Litz stator can achieve very high efficiency but limited specific power
  - Reach thermal limit due to relatively weak B field produced by rotor
- Magnets are heavy and relatively thick (see appendix)
  At ≥ 99.4% efficiency, magnets are:
  - 45% to 55% of total mass (Helmholtz & outer rotor)
  - 60% to 70% of total mass (3 rotor)
- Only Helmholtz meets goal



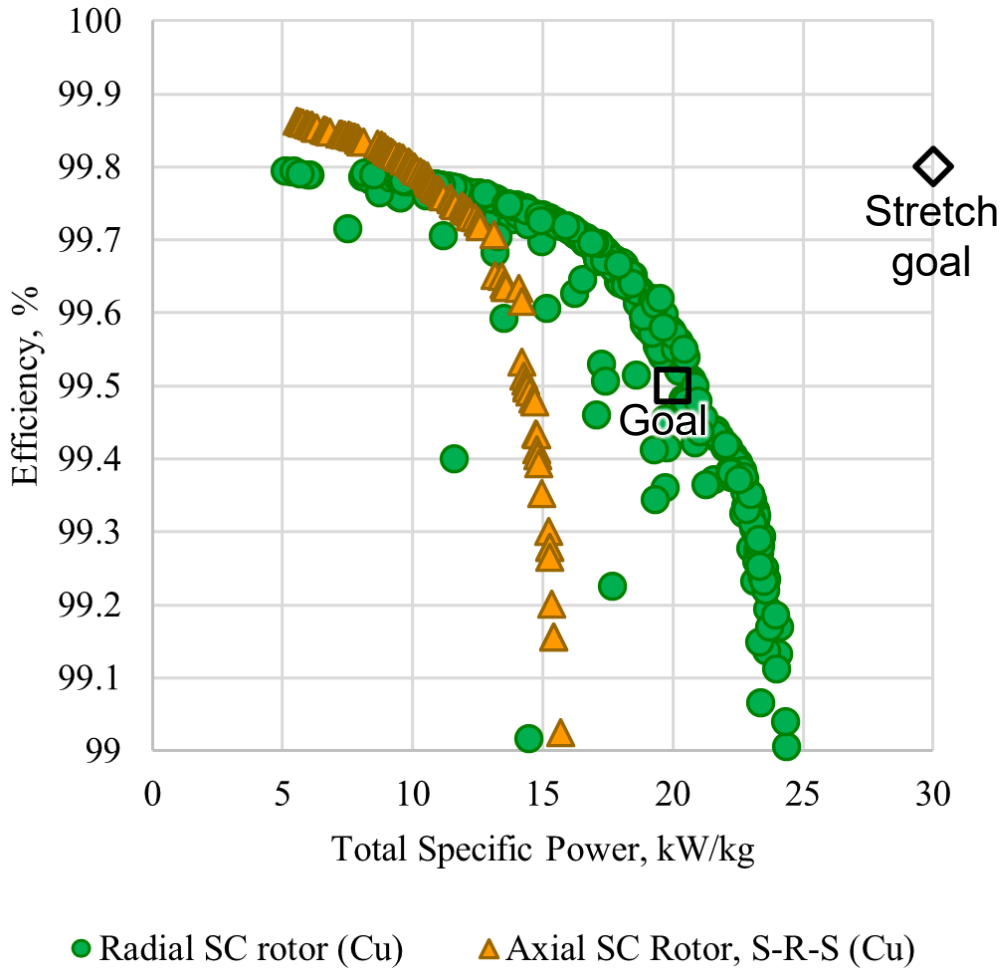

*Note: efficiency of outer rotor & 3-rotor configurations is artificially high by 0.01% to 0.03% due to neglect of windage loss*

**Takeaway**

Helmholtz configuration carried forward as a configuration finalist based on performance

# Results – Superconducting Rotors

- Again, axial flux configurations limited by stiffness of stator's vacuum & fluid containment vessels
  - Rotor-Stator-Rotor configuration did not close
- Axial Stator-Rotor-Stator outperforms axial Rotor-Stator-Rotor because
  - Rotor heat load smaller
  - Torque produced on both sides of rotor
  - Each of 2 stators is thinner and easier to cool
- Only radial flux, inner SC rotor meets goal

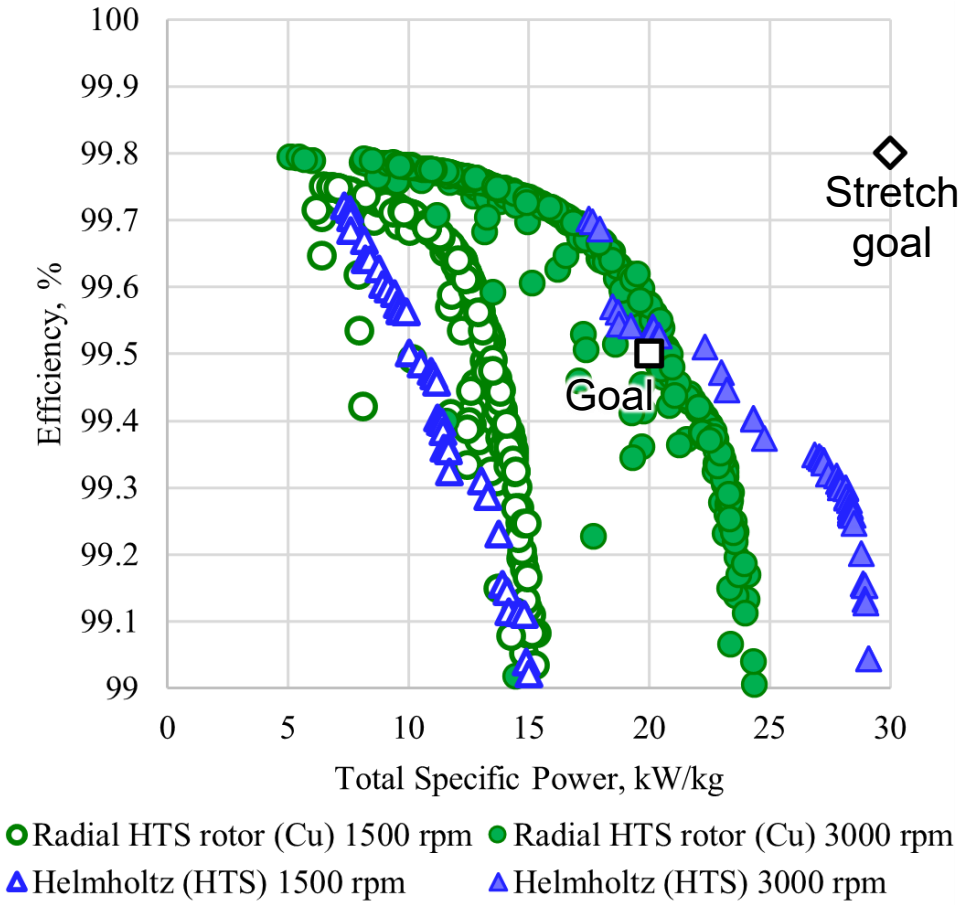



**Takeaway**

Radial flux inner rotor configuration carried forward as a configuration finalist based on performance

# Results – Configuration Finalists

- Configuration finalists also optimized at 1,500 rpm
- Neither design predicted to meet specific power goal at lower speed
- No clear winner considering fidelity of codes → configuration selection needs to consider additional factors
  - At 3,000 rpm – equivalent performance in vicinity of goal
  - Radial flux inner HTS rotor configuration scales to lower speed somewhat better



# Qualitative Comparison of 2 Finalists

| | Helmholtz (PM rotor) | Radial, Inner Rotor (SC rotor) |
|---|---|---|
| **Can meet technical objectives** | ✓ | ✓ |
| **Stator conductor** | Better performance with HTS | Better performance with Cu litz |
| **Input to community** | Novel architecture development<br>REBCO AC loss performance | Cryogenic Cu litz wire performance<br>Cryocooler development<br>Rotary power transfer development |
| **Key challenges** | Assembly of large PMs<br>Vacuum vessel in air gap<br>Cantilevered rotor & stator<br>Packaging of stator feedthroughs | Needs rotor cryocooling<br>Needs power transfer onto rotor<br>May need rotary vacuum seal(s)<br>May need vacuum vessel / magnetic shield in air gap |
| **Key benefits** | Simpler rotor cooling<br>Relaxed inverter output distortion limit | Lower cryogenic heat load<br>Reduced structural complexity & better rotordynamics |
| **Bottom line** | Novel architecture that enables ideal SC in stator<br>Less mature, higher uncertainty | Established architecture<br>Leverages prior work |

Both configurations worthy of selection, but radial, inner rotor chosen considering info shown, project's risk tolerance, and additional internal factors

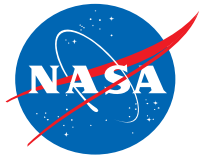
# Conclusions & Future Work

## Conclusions

- Motor efficiency goal derived for compatibility with future H2-burning engines: ≥ 99.5% for moderate to highly electrified aircraft
- Using gaseous He coolant instead of liquid cryogens yields a meaningful reduction in motor performance but it can be worth it
- The Helmholtz (PM rotor) and radial flux, inner HTS rotor configurations are competitive in terms of performance and qualitative factors – both clearly outperform other configurations studied in detail

## Future work

- Conduct detailed design of 2 MW radial flux motor with HTS rotor – the Cryogenic High-power Integrated Low Loss (CHILL) motor
- Develop CHILL drive, pair with motor, and test at full power and coolant temperatures between about 35 K to 115 K



# Acknowledgements

This work was funded by the Aircraft Electrification Subproject

Aeronautics Research Mission Directorate

Advanced Air Vehicles Program

Advanced Air Transport Technology Project

Aircraft Electrification Subproject

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# Overview of Electromagnetic Analysis

**Electromagnetic analysis**

| | Helmholtz config. | All other config. |
|---|---|---|
| Dimension | 2D | |
| Temporal fidelity | Pseudo time-stepping | |
| Magnetic field sources | All (rotor produced & self field from full stator winding) | |
| Mechanical air gap size | 1 mm (outer gap), 1.5 mm (inner gap) | ≥ 1 mm |
| Superconductor model | Full fidelity (temperature-, field-, and field angle-dependence) | |
| Superconductor current safety factor | ≥ 1.5 | 1.5 |
| Material properties of iron, permanent magnet, and litz wire | Temperature-dependent | |
| Winding type | 3- to 9-phase (concentrated) | 9-phase (distributed) or 3- to 9-phase (concentrated) |

## Losses considered

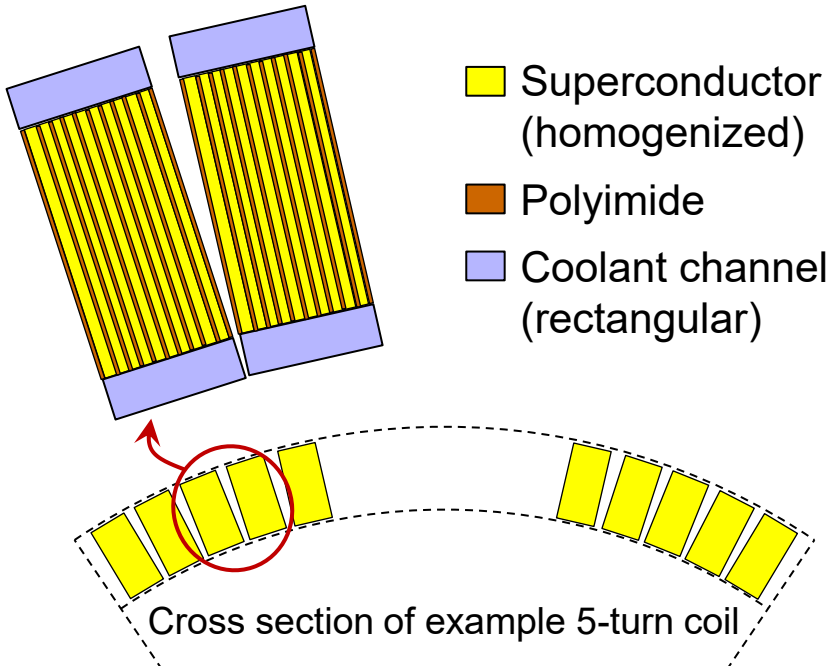
- *In Litz wires*: AC resistive & proximity eddy current losses
- *In superconductors*: hysteresis, eddy current, coupling, (also transport in HTS)
- Bearing
- Windage (Helmholtz motor only)
- Pumping fluid through motor
- Cryocooler (fully cryo motors)
- Iron (where required)
- 1.5 kW for rotary vacuum seals (where required)

# Overview of Thermal Analysis

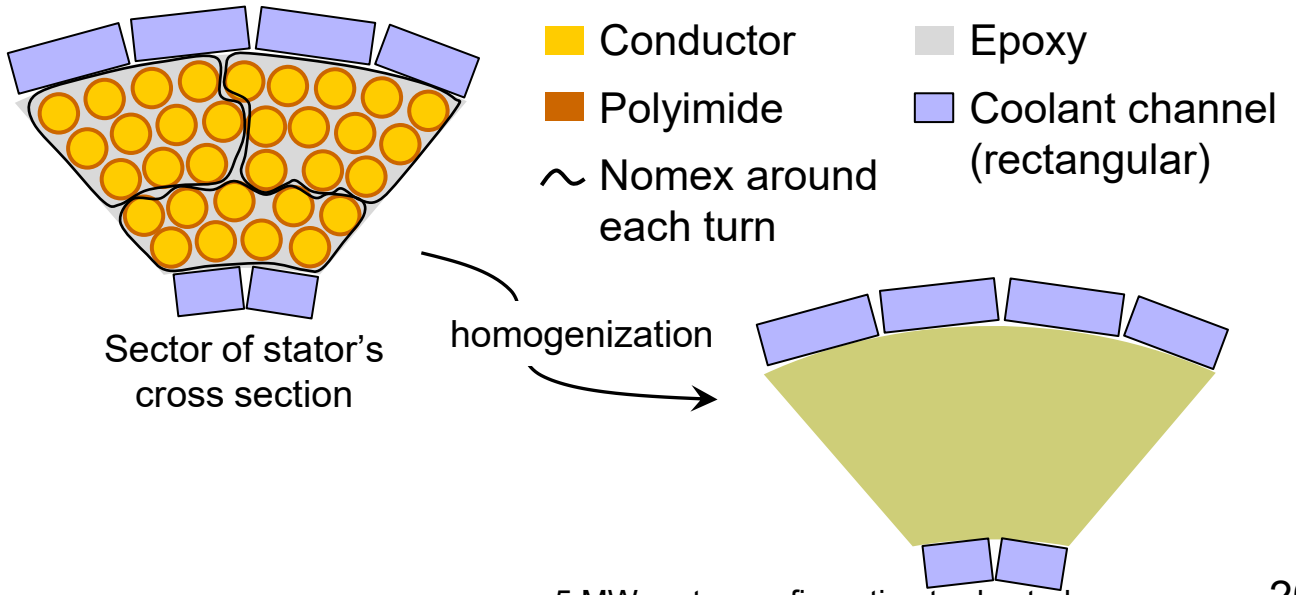
**Thermal analysis**

| | Helmholtz config. | All other config. |
|---|---|---|
| Dimension | 2D | 1D |
| Geometry | See below | |
| Temporal fidelity | Time averaged | |
| Spatial fidelity | Loss per SC tape | Spatially averaged |
| Coolant temperature | At inlet | At outlet |
| Temperature-dependent properties? | Yes | Conductor resistivity & coolant only |

## Helmholtz




## Other configurations



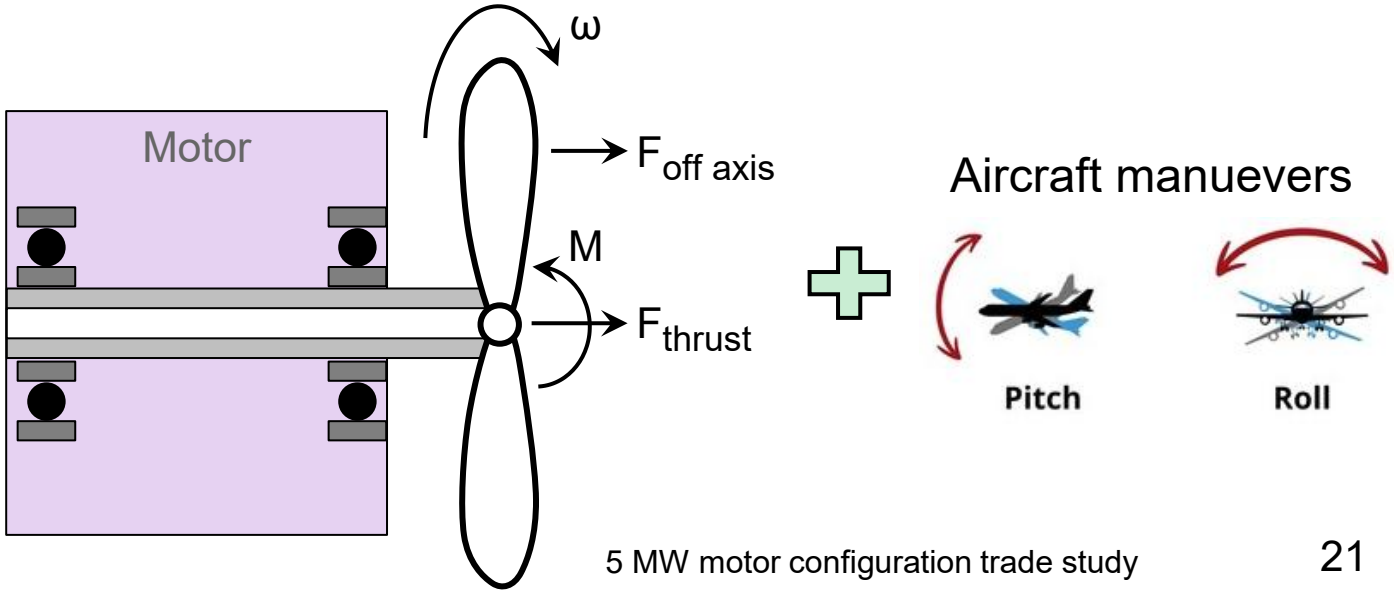
# Overview of Mechanical Analysis

**Mechanical analysis**

| | All configurations |
|---|---|
| Dimension | 2D |
| Geometry | Simple cylinders & discs |
| Materials | G-10 (vessels in mag field), 17-4 stainless (shaft), Ti-6Al-4V (other structures) |
| Temporal fidelity | Static |
| Loads | Air & coolant pressures, torque, centrifugal, prop loads (see below) |
| Bearing reliability & life | 90% to reach 5,000 hour life |
| Temperature-dependent properties? | No |

- Vacuum & fluid containment vessels sized for buckling (external pressure) or hoop stress (internal pressure)
- Manufacturability considered: lower limit of 1.5 mm on section thickness
- Total mass estimated, including:
  - Electromagnetic
  - Shafts & bearings
  - Vacuum vessels, fluid containment, fluid, & rotors
  - Cryocooler & thermal connection to it
  - 10 kg for miscellaneous components

Loading for bearing & shaft sizing

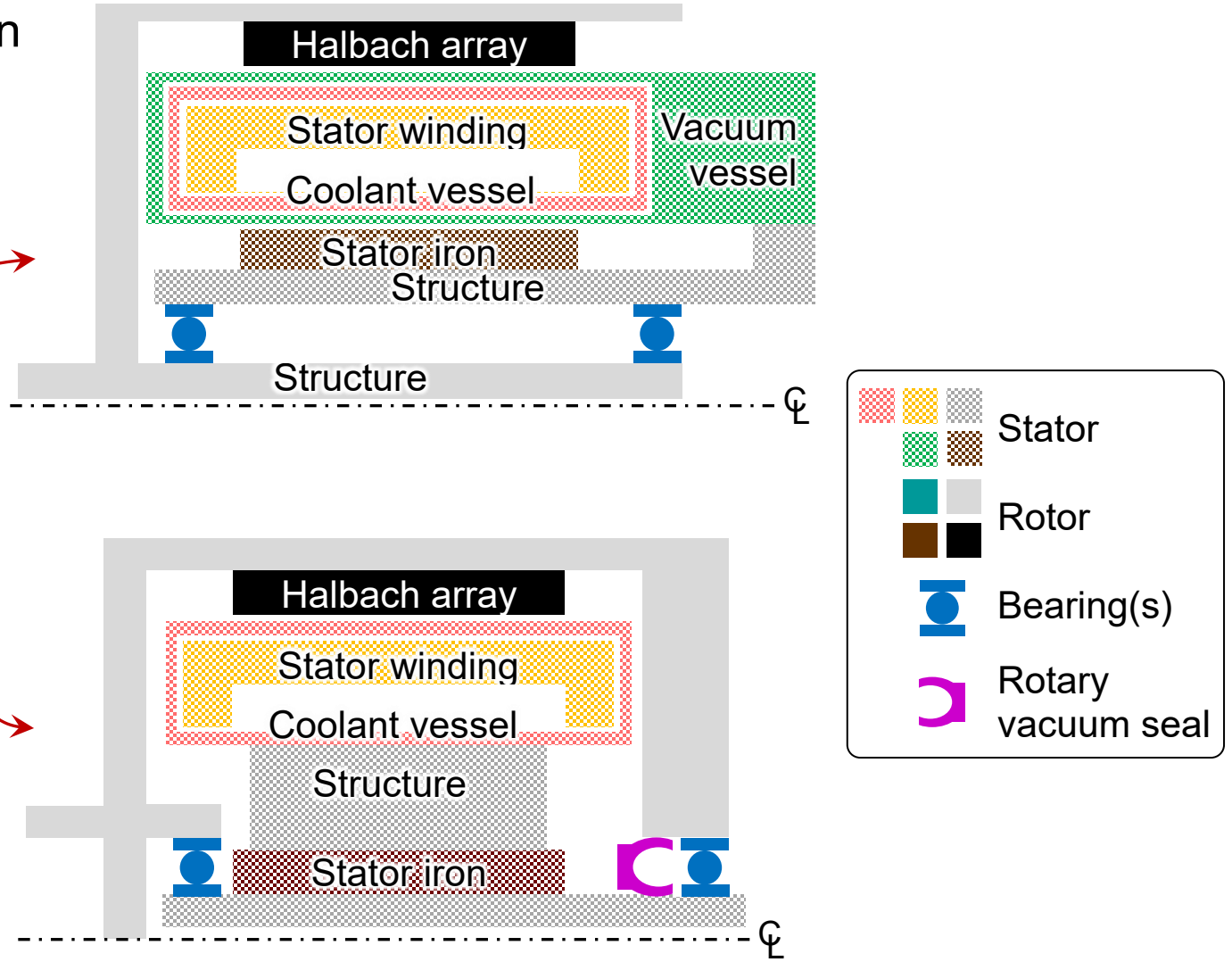



5 MW motor configuration trade study

# Motor Configurations

- Distributed winding in all but 1 configuration

| # | Motor type (rotor field source) | Flux direction | Construction | |
|---|---|---|---|---|
| 1 | Partial cryo (permanent magnet) | Radial | Outer rotor | Stator is vacuum vessel |
| 2 | | | | Rotor is vacuum vessel |
| 3 | | | Helmholtz | |
| 4 | | Axial | Rotor – stator – rotor | |
| 5 | | Radial + axial | 3-rotor, no iron | |
| 6 | Fully cryo (supercond.) | Radial | Inner rotor | |
| 7 | | Axial | Stator – rotor – Stator | |
| 8 | | | Rotor – stator – rotor | |



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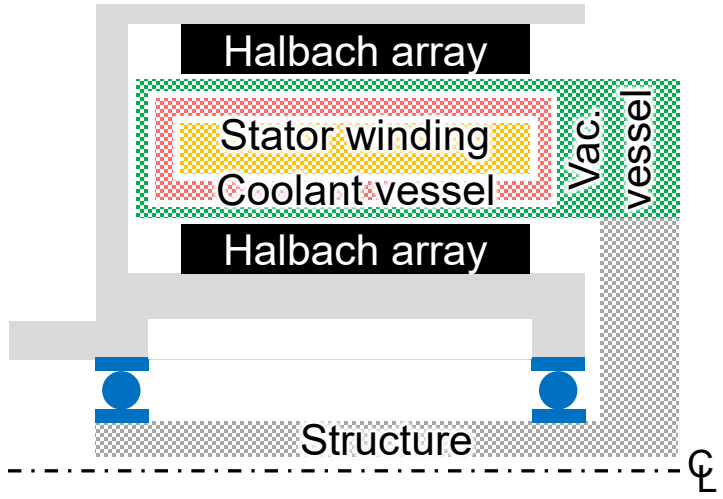
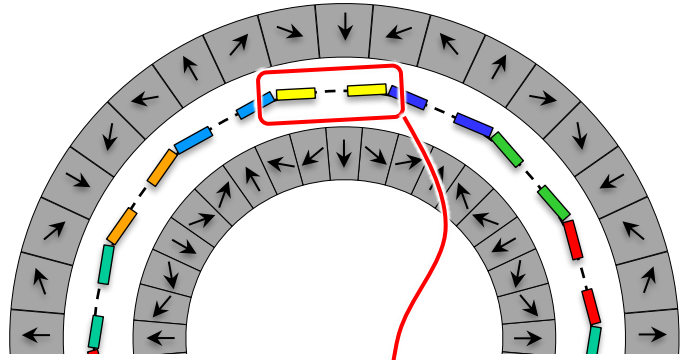
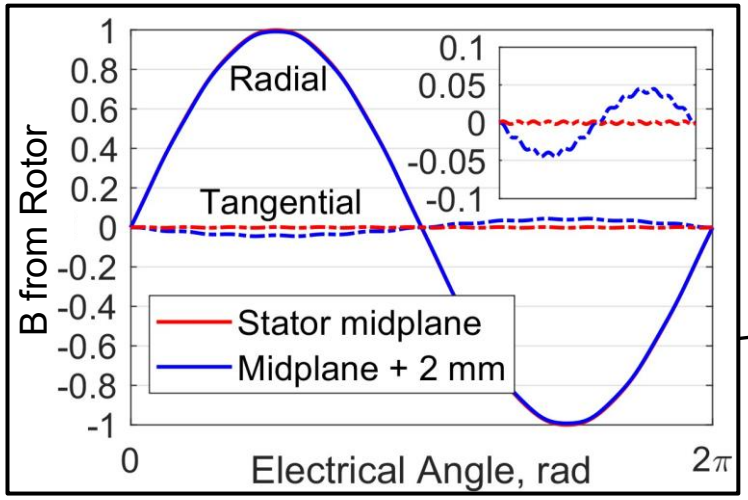
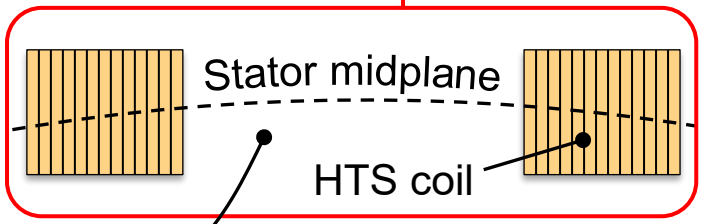
Radial flux Helmholtz machine with permanent magnet rotors
(*patent pending*)





# Motor Configurations

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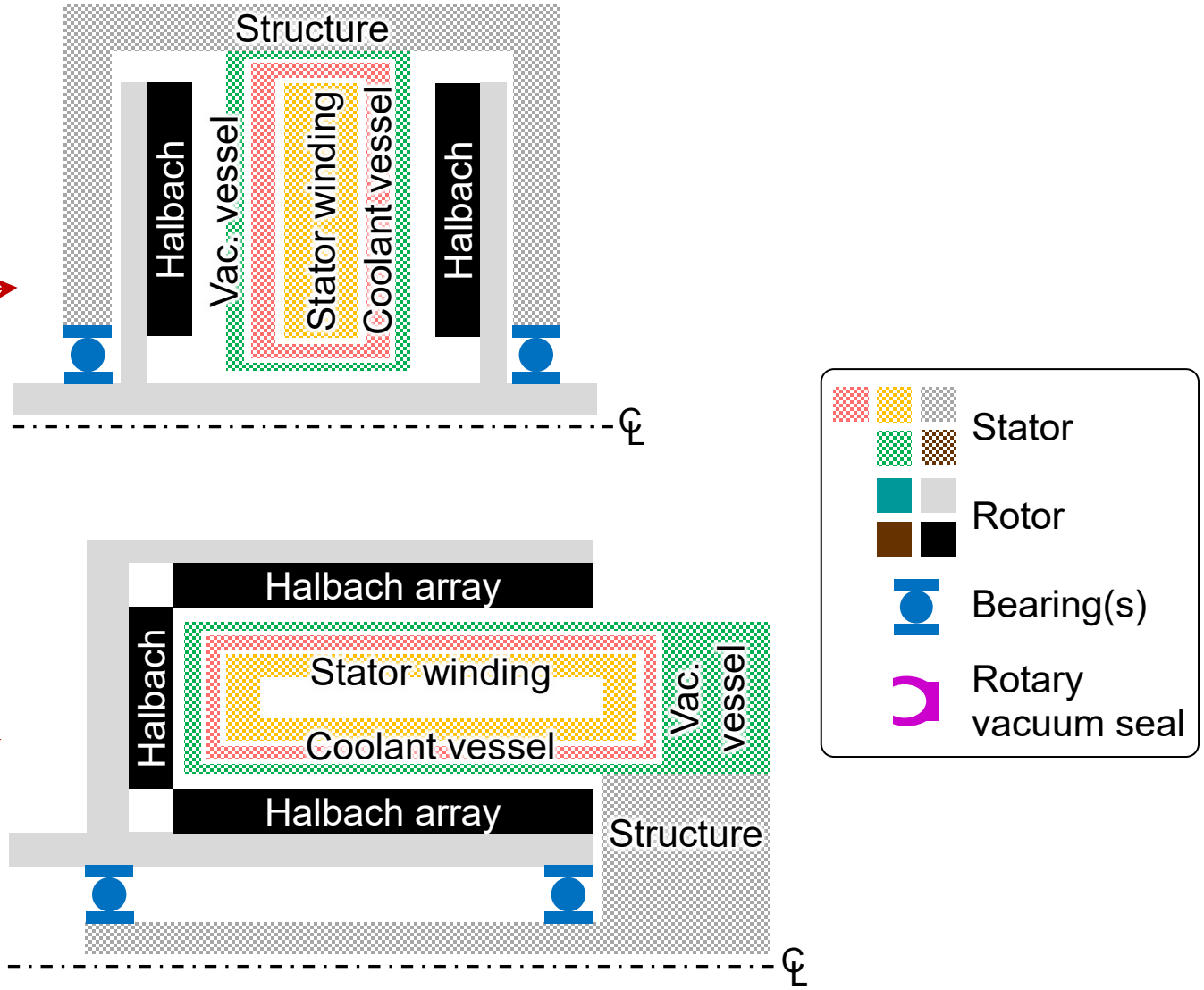

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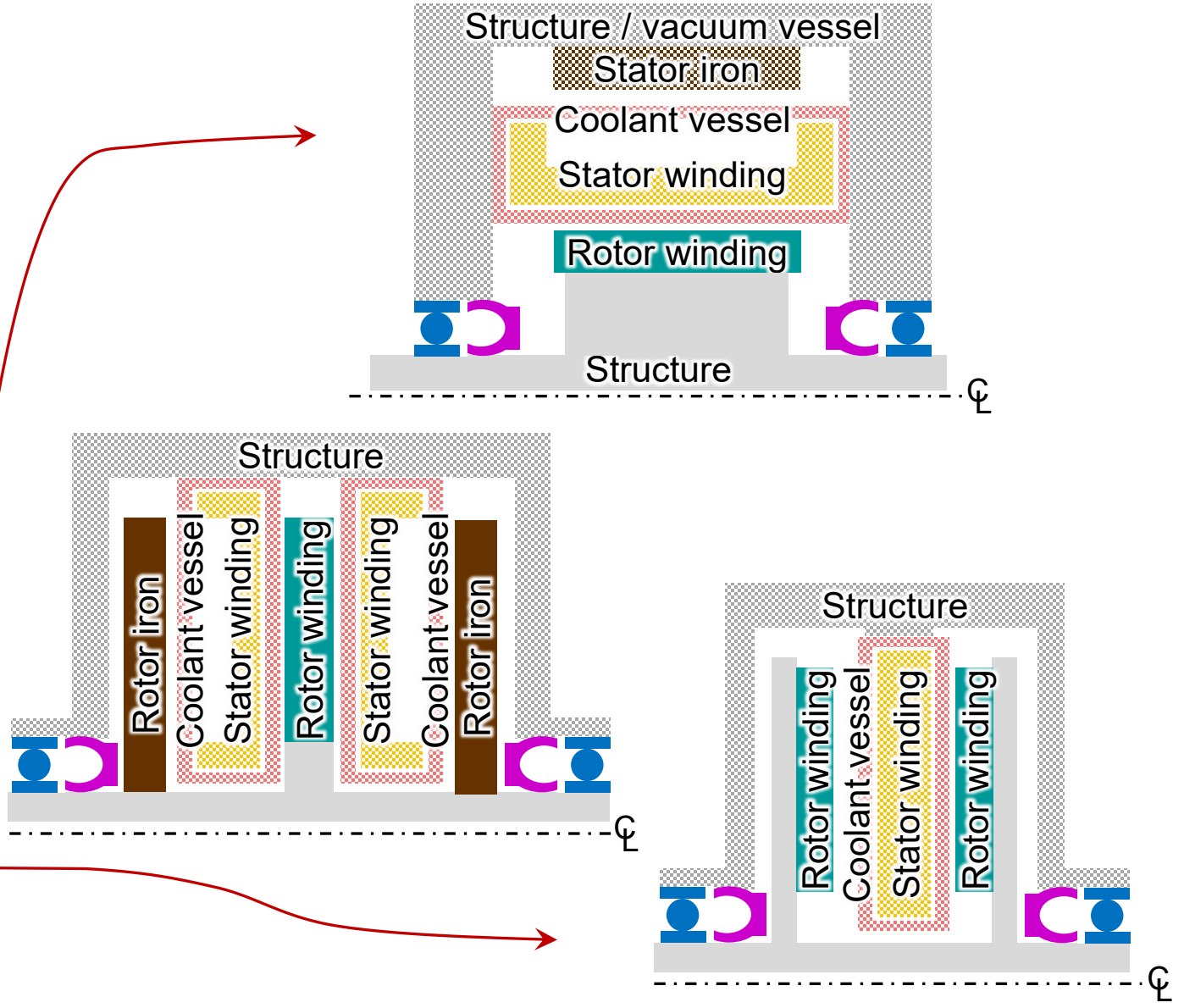
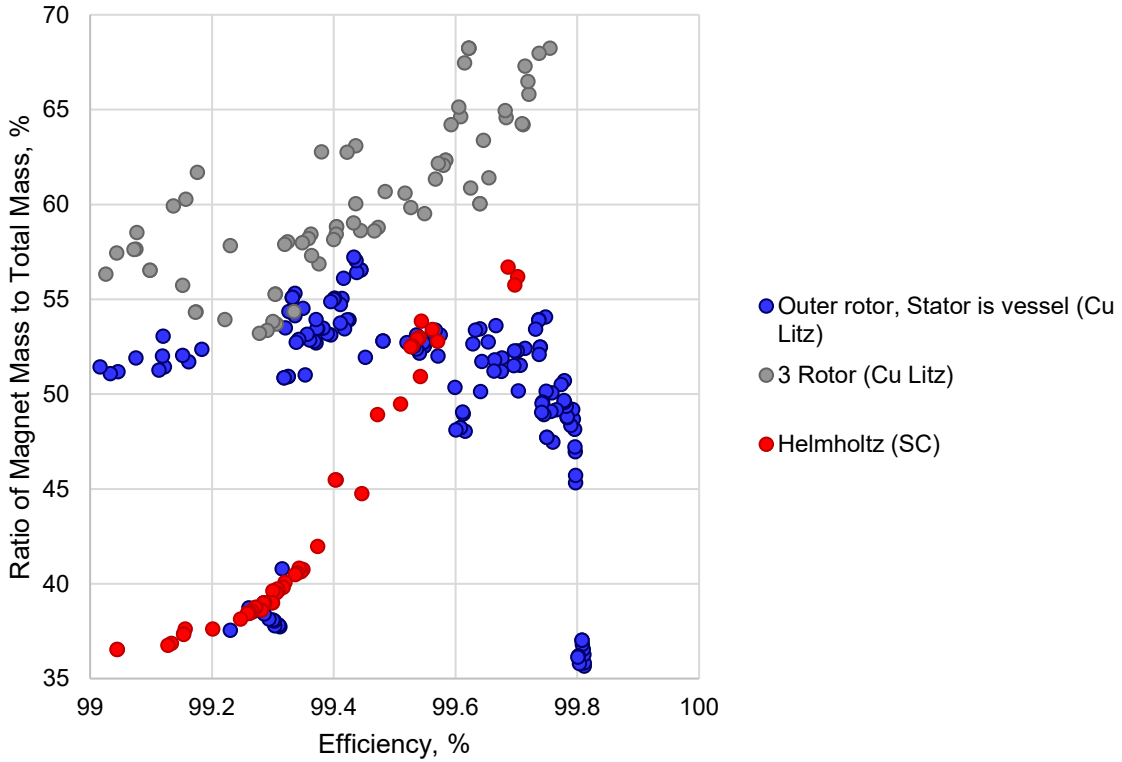
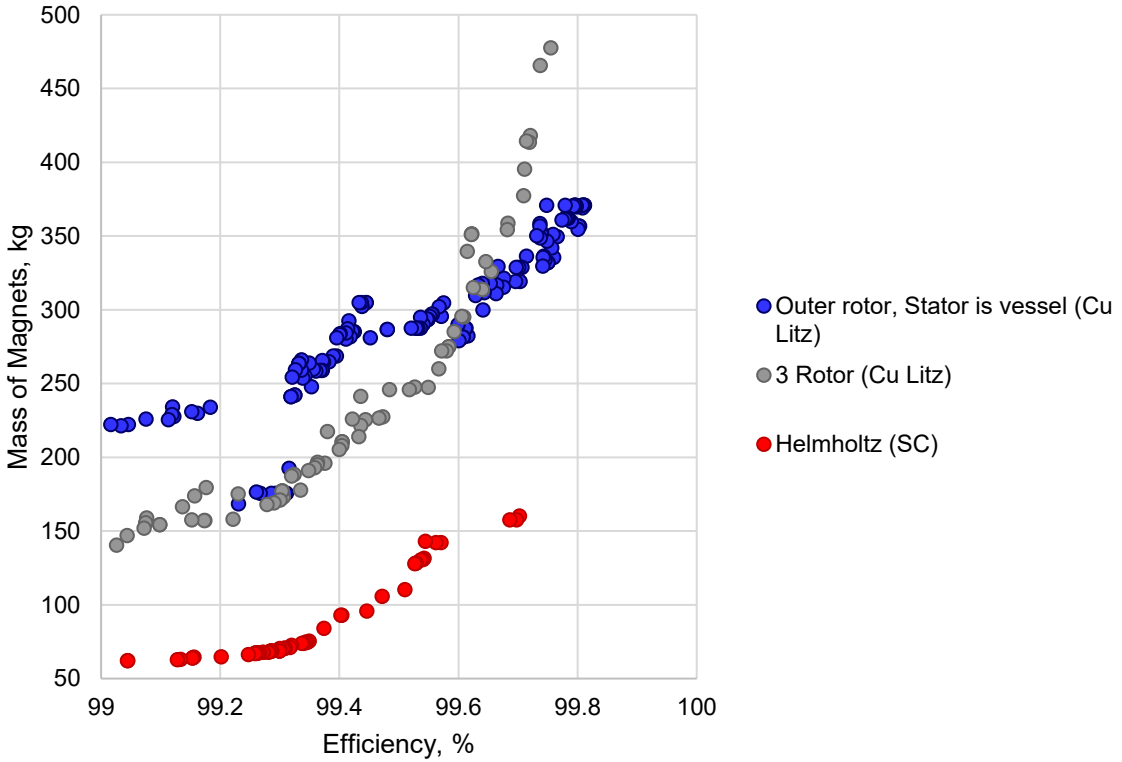


# Comparison of Motors with Permanent Magnet Rotor (Partially Cryo)

- Magnets are heavy and thick
  (often about 50% to 65% of total mass)

**3,000 rpm**



# Stator Windings for Axial Flux Motors

Configuration 7 →

Fig. 3 "Distributed" stator topology. Windings have no skew in the active region of the machine and correspondingly complex end turn geometry.

Configuration 8 →

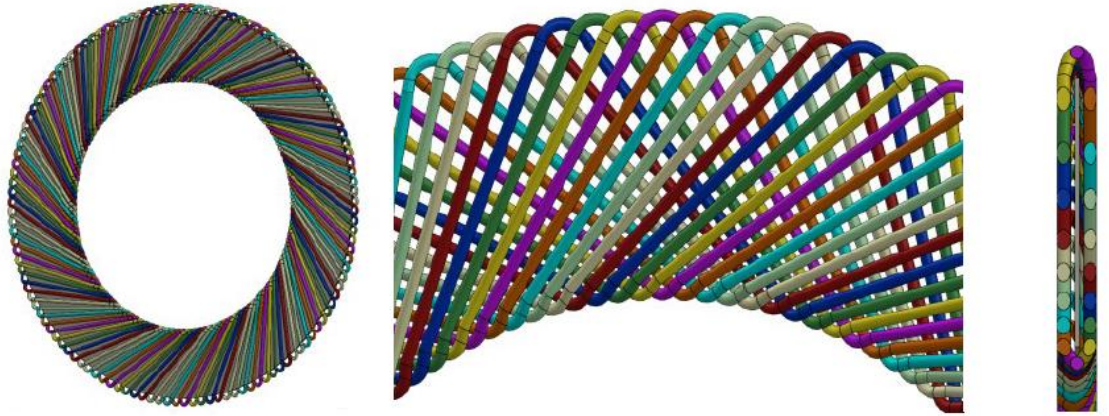


Fig. 4 "Zig-Zag" stator topology. Windings are skewed by approximately one pole arc in the active region of the machine in order to minimize end winding complexity and mass at the cost of reduced torque production due to the winding skew.