Lessons learned from a cryogenic motor configuration study for aircraft propulsion

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Motivation & Direction

Enable an American aviation ecosystem powered by domestic LNG and advanced electrification

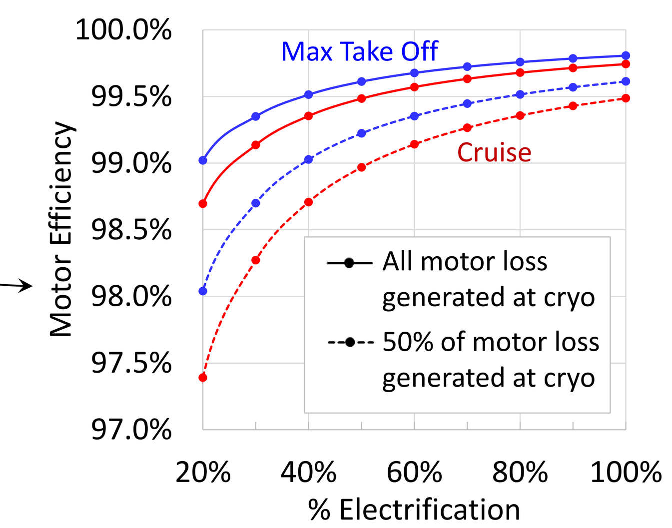
High-power electrified propulsion ▪ Advanced engine cycles for cryo fuel ▪ Radical airframe technologies ▪ Propulsion airframe integration

- **Economic benefits:** reduced fuel consumption ▪ decreased energy costs & increased cost stability ▪ abundant domestic supply ▪ U.S. export advantage ▪ shared fuel infrastructure across transportation sectors
- **Societal benefits:** global access to air travel can continue to grow
- **Environmental benefits:** reduced emissions ▪ pathway to fully renewable production
- High-power electrification focused on single- and twin-aisle aircraft (~150+ passengers)

Develop a multi-MW superconducting motor & cryogenic drive to evaluate whether the technology is ready to contribute to electrified aircraft propulsion
5 MW 'vision' motor ▪ 3 MW demonstration motor

Specifications for 'Vision' Motor

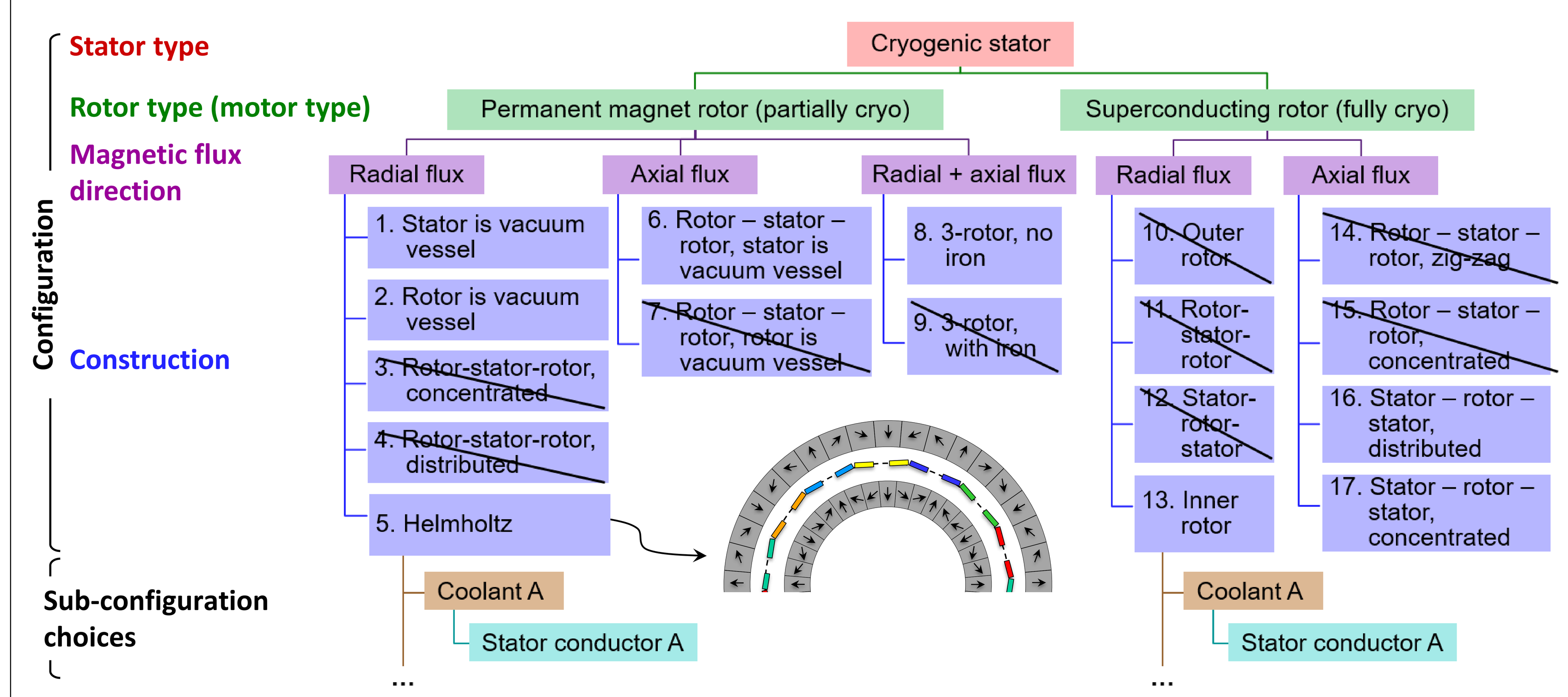
Parameter	Goal	Stretch Goal
Continuous power, MW	5	-
Rated speed, rpm	1,500 – 3,000	-
Efficiency at rated speed	≥ 99.5%	≥ 99.8%
Continuous specific power, kW/kg	≥ 20	≥ 30
DC bus voltage (relative to neutral), V	≥ ±270	≤ ±1,000
Rated voltage of insulation, V	≥ 1,000	2,000
Diameter ratio of outer mold line to prop with tip speed of 295 m/s	≤ 34%	-



Estimated motor efficiency required to avoid extra cryocooling in LH2-burning aircraft

- Motor for directly driving propeller / fan
- Upper limit of ±1,000 V to limit material development & electronics packaging issues
- Considered either superconductor, high purity aluminum, or copper Litz as stator conductor
- Technology Readiness Level (TRL) advancement prioritized over performance

Motor Configurations Studied



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)

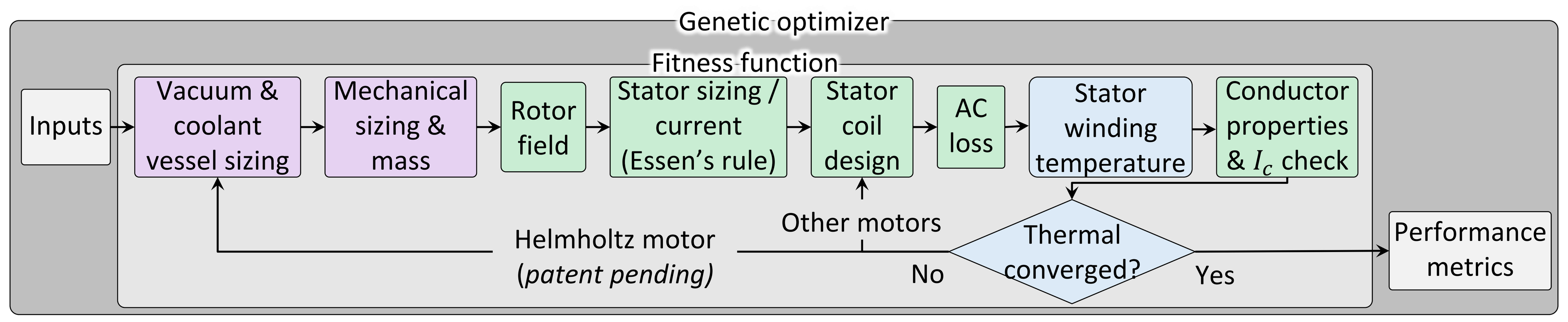
Electromagnetic analysis

	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 loading factor	≤ 67%	67%
Material properties	Temperature-dependent (iron, magnets, & Litz wire)	
Winding type	3- to 9-phase (concentrated)	9-phase (distributed) or 3- to 9-phase (concentrated)

- Known issue, but not yet corrected: stator iron does not influence magnetic fields

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 (when used)
- 1.5 kW for rotary vacuum seals (when used)

Motor Design Code

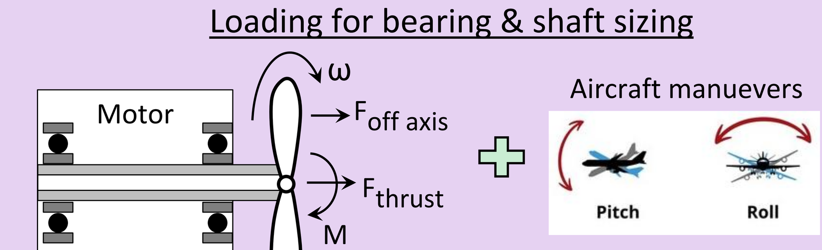


Mechanical analysis

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

- Vacuum & fluid containment vessels sized for buckling or hoop stress
- Manufacturability: ≥ 1.5 mm section thickness
- Total mass estimated: EM, shafts & bearings, pressure vessels, fluid, rotors, cryocooler & thermal connection to it, 10 kg for fasteners/other

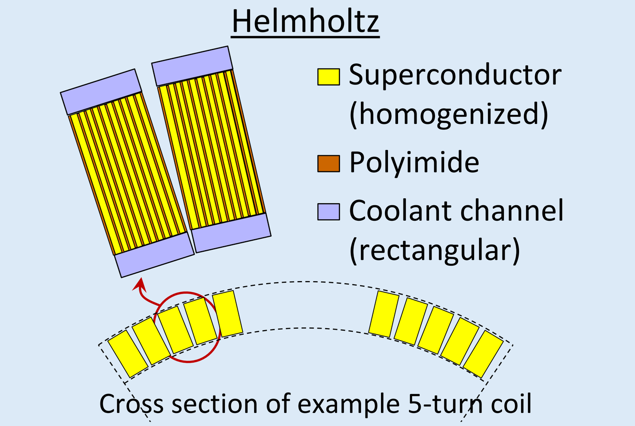
Loading for bearing & shaft sizing



Thermal analysis

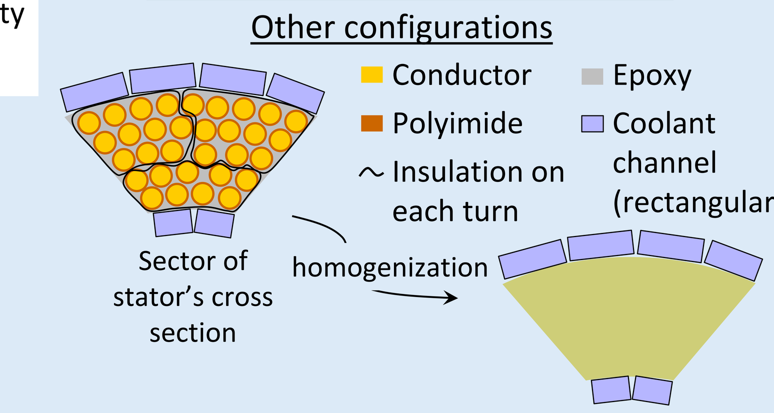
	Helmholtz config.	All other config.
Dimension	2D	1D
Geometry	See below	
Temporal fidelity	Time averaged	
Spatial fidelity	Loss per SC tape	Spatially averaged
Coolant temperature	At inlet	At outlet
Temperature-dependent properties?	Yes	Conductor resistivity & coolant only

Helmholtz



Cross section of example 5-turn coil

Other configurations

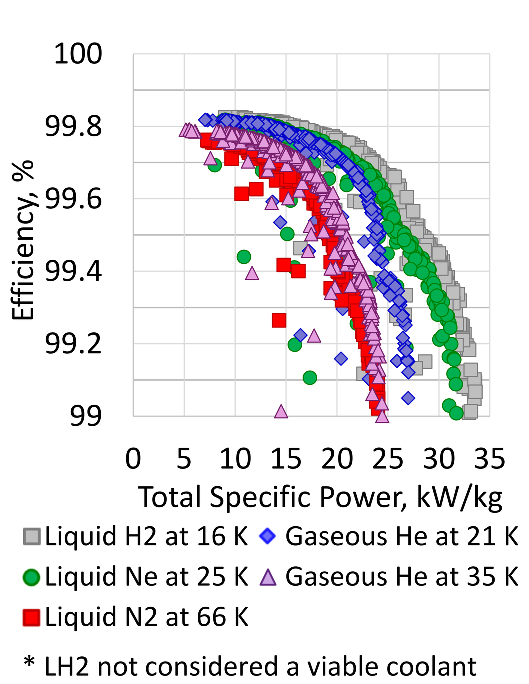


- Flooded cooling of stator (winding surface directly cooled on one active face [3-rotor & axial flux] or inner & outer diameters [radial flux])
- On-board cryocooler in rotor – notional cryocooler based on Carnot efficiency & mass of commercial coolers

Performance of Configurations

- GHe selected due to its lack of flammability, much lower density, lack of phase change, no potential for cavitation issues, and availability
- Copper litz wire was selected for the stator due to high performance as modeled, ability to operate warmer, and broad availability
- There is still uncertainty in superconductor AC loss modeling. With improvements in superconductors designed for low AC loss and in loss modeling, superconductors may outperform copper Litz wire in the future, particularly at temperatures enabled by LH_2

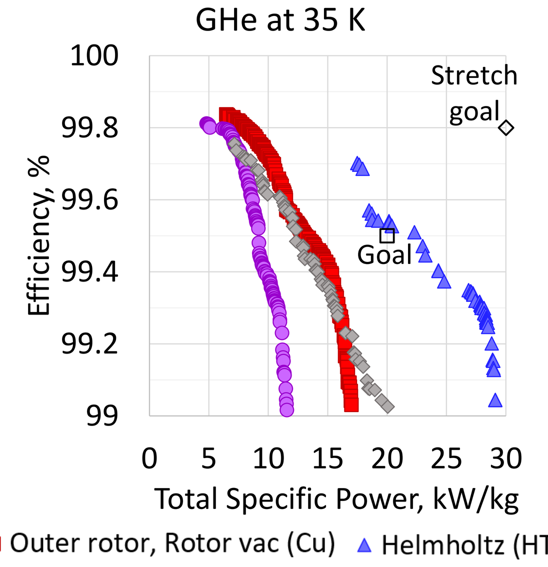
Impact of stator coolant



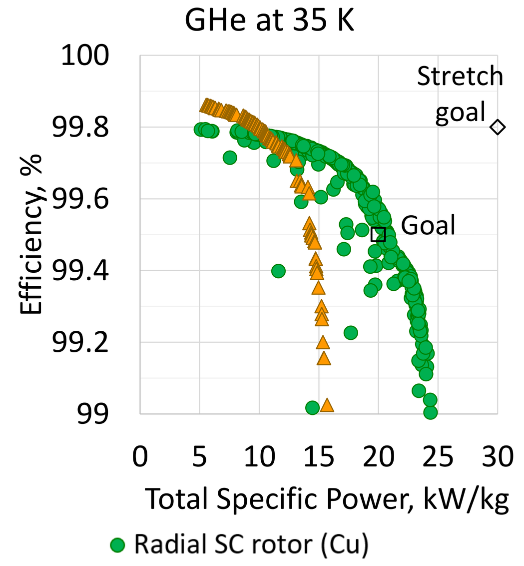
* LH2 not considered a viable coolant but is included for comparison

Lesson
- At ≤ 70 K, stator coolant primarily impacts specific power

Permanent magnet rotors
GHe at 35 K

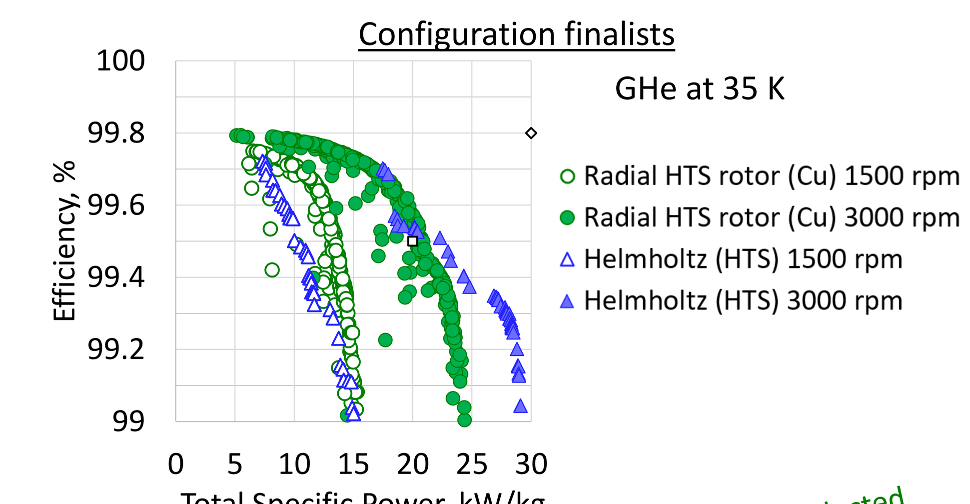


Superconducting rotors
GHe at 35 K



Lessons
- Motors with PM rotors can achieve very high efficiency, although the magnets are heavy (often ~40% to ~65% of total mass)
- Axial flux designs are limited by buckling constraints on thickness of vacuum vessel(s) in air gap

Configuration finalists



	Helmholtz (PM rotor)	Radial, Inner Rotor (SC rotor) (selected)
Performance	✓	✓
Stator conductor	Better performance with HTS	Better performance with Cu litz
Input to community	Novel architecture development REBCO AC loss performance	Cryogenic Cu litz wire performance Cryocooler development Rotary power transfer development
Key challenges	Assembly of large magnets Vacuum vessel in air gap Cantilevered rotor & stator Packaging of stator feedthroughs Cooling below LNG temperature	Needs rotor cryocooling Needs power transfer onto rotor May need rotary vacuum seal(s) May need vac. vessel / mag. shield in air gap
Key benefits	Simpler rotor cooling Relaxed inverter output distortion limit	Lower cryogenic heat load Less complex structurally & better rotordynamics
Bottom line	Novel architecture enabling ideal SC in stator Less mature, higher uncertainty	Established architecture Leverages prior work

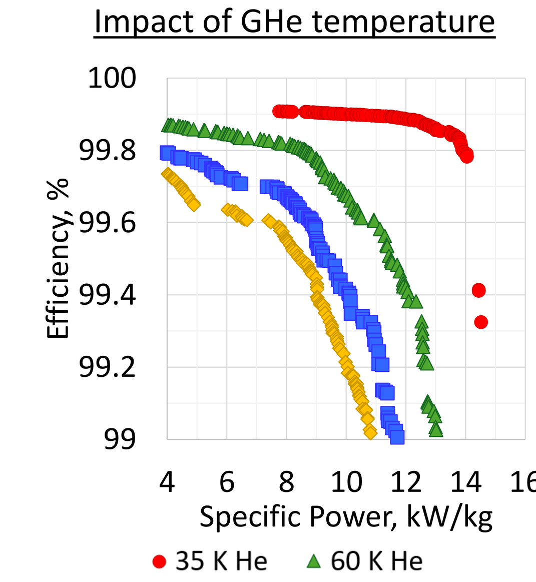
Both configurations worthy of selection, but radial, inner rotor chosen considering info shown, project's risk tolerance, and additional internal factors

Impact of Design Modifications

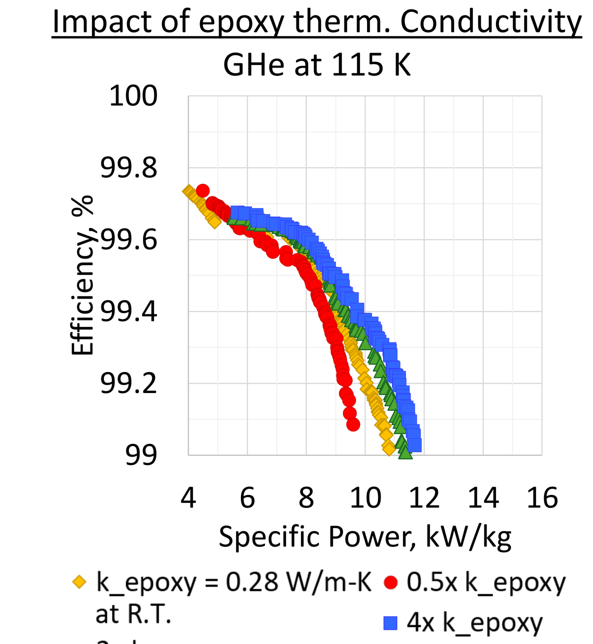
motivation: refine predictions for selected configuration & investigate performance limitations

Updates to design code implemented prior to obtaining results below:
- Refined Litz wire design
- Added temperature-dependent thermal properties where missing (incl. epoxy thermal conductivity)
- Added GHe and winding temperature variation along cooling channels
- Rotor: switched to COTS cryocooler (36 K base temp.) & revised heat loads

Impact of GHe temperature

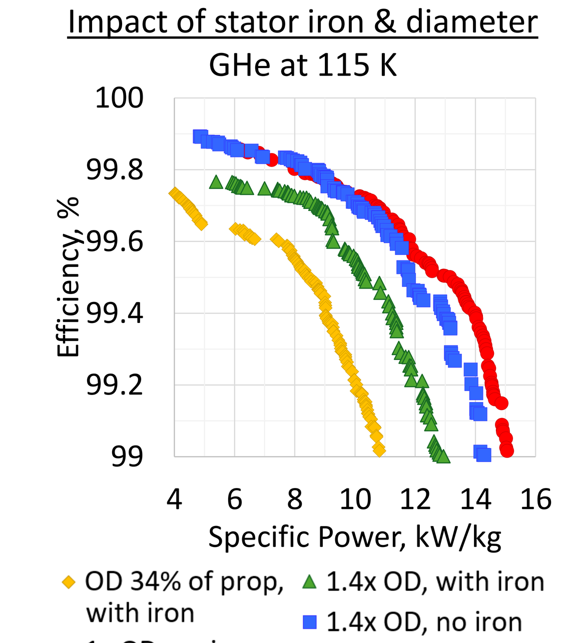


Impact of epoxy therm. Conductivity
GHe at 115 K



Lessons
- Coolant temperatures ≤ 60 K provide significant benefit over operation near LNG temperature
- It is challenging to exceed 15 kW/kg with the design and assumptions used

Impact of stator iron & diameter
GHe at 115 K



Impact of stator's pressure vessel material
GHe at 115 K