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Wed-Mo-Po3.12

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Superconducting Synchronous Motors for Electric Ship Propulsion

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Summary

We propose a notional design for a high-torque-density (66 Nm/kg), high efficiency (99%) 36 MW, 120 rpm motor for ship propulsion. The synchronous motor uses LTS field coils to create a minimum of 2 T magnetic field in the air gap of the motor. The LTS motor is substantially lighter, more compact, and far more cost effective than other compared approaches. A significant feature of the LTS motor is reduction in radial forces between the field and armature by two orders of magnitude compared to a conventional motor. The motor promises significant cost and performance improvement. Conductor requirements, options, and electromagnetic features such as quench protection and cryogenic support options are discussed.

Introduction

- **Advantages of SC rotating machines: higher efficiency, reduced size and weight, simplified load regulation, ability to ramp the field down for maintenance, reduced noise, etc.**
- **Challenges: (a) high conductor price; (b) poor reliability and frequent maintenance of the cryogenic system, (c) winding instability due to small temperature margins; (d) field harmonics generated by stator; (e) issues for various rotating machine designs including but not limited to the need for high-current brushes in dc homopolar machines, tight air gap requirements, and low reactance.**
- **Commercially-competitive superconducting synchronous motor: must be rather large, over 20 MW power, relatively low speed ~100 rpm**
- **HTS machines are technically feasible. Preclude commercialization: HTS conductor price, restrictions of operating at high magnetic field, poor mechanical properties, and high manufacturing and maintenance**
  - HTS machines so far: technology Demos, not Prototypes
  - HTS Demos were not optimized for volume production. Not addressed: manufacturability, reliability, maximized maintenance intervals, minimized cost or optimized performance of the whole system
- **NbTi field coils for rotating machinery: potential for commercialization**

Field coils: electromagnetic design

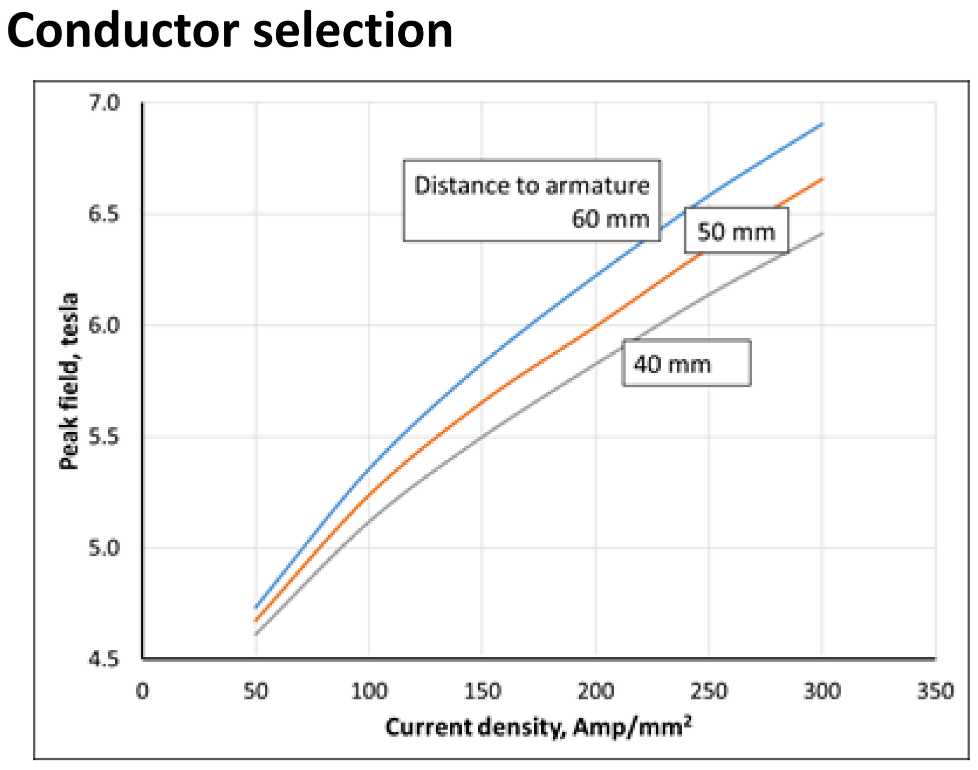
Field coil parameters

Item	Value
Field coil count	30
Coil length	141 cm
Conductor length per coil	2.5 kAmp-km
Conductor length per motor	75 kAmp-km
Peak field on conductor, tesla	7 tesla
Average current density	200 Amp/mm²
Stored energy total	17 MJ

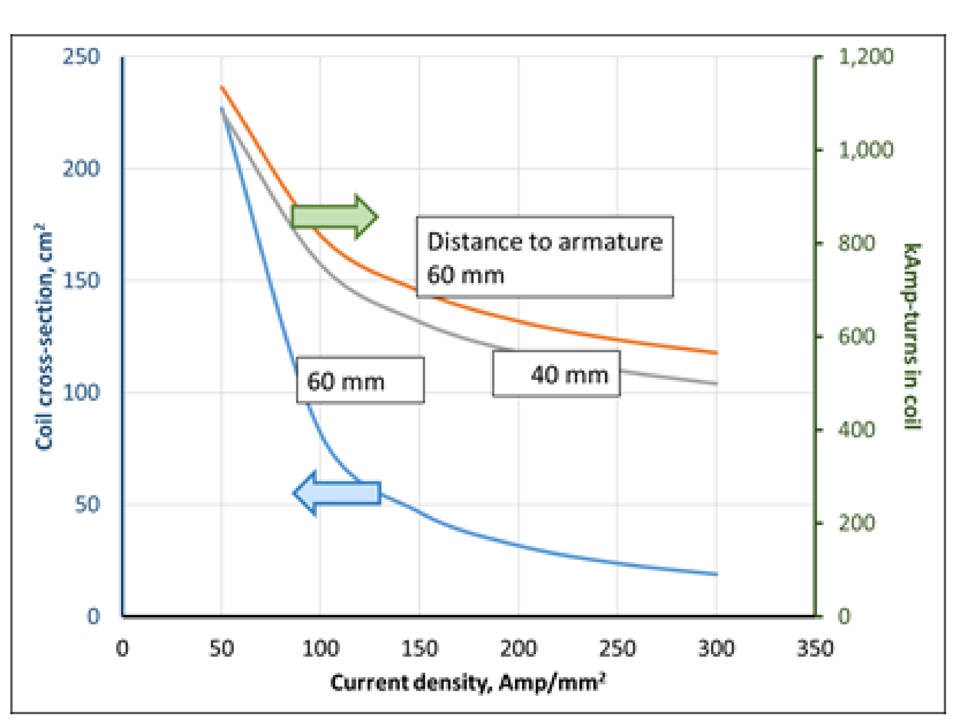
Notes

- Higher-efficiency units require longer coils, higher conductor length, higher stored energy
- Field coil count: Trade-off (a) lower weight and higher efficiency for fewer coils at the expense of higher ac losses and field harmonics
- Higher current density for more efficient design

Conductor selection



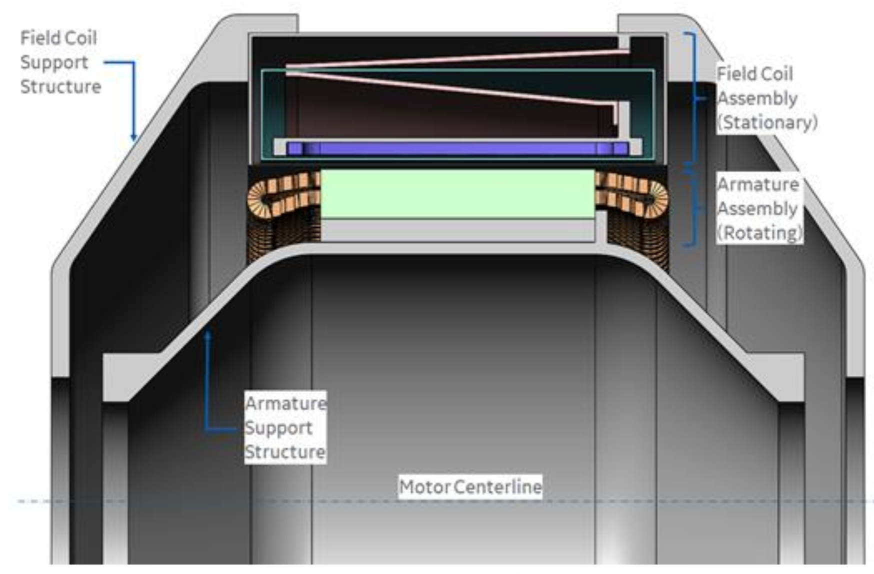
Peak field on Field coils vs J_{avg}



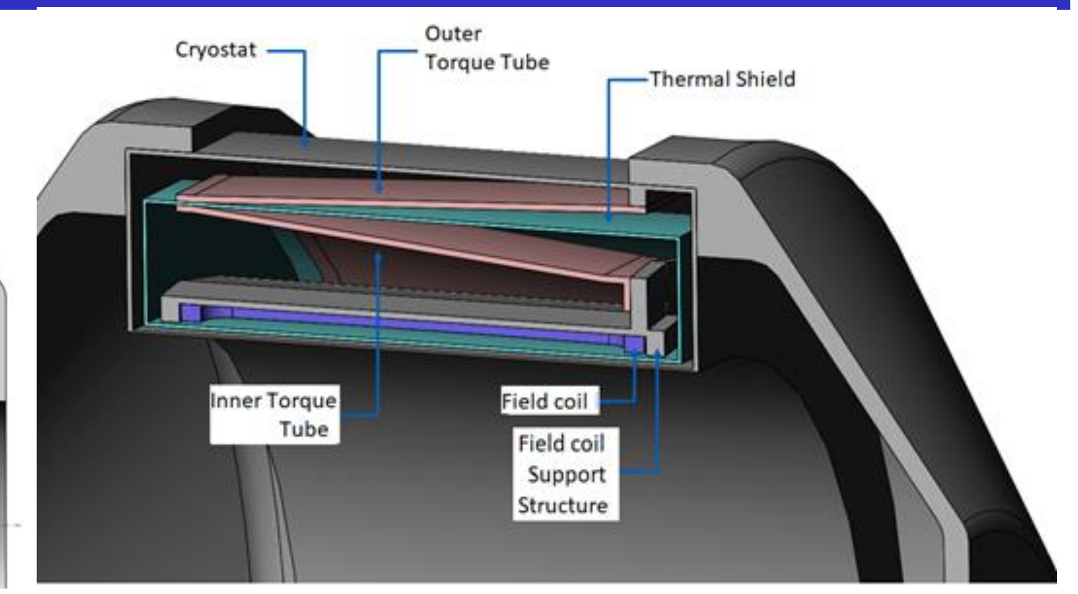
Coil cross-section and conductor length vs J_{avg}

- Current density J_{avg} trade off:
  - Higher J_{avg} **:** less conductor, compact configuration at a penalty of higher peak field
- Competitive superconducting motors may require high current density ~200 Amp/mm2 in the superconducting field coils, with peak field in the range of 6.5 T to 7.5 T
  - At current density below 125 Amp/mm2, the coils become very large and expensive
- Coil cross-section ~30 cm², ~600 kAmp-turns
- Commercially available SC wire with Cu : NbTi ratio in the range of 2 : 1 to 3 : 1

LTS motor configuration



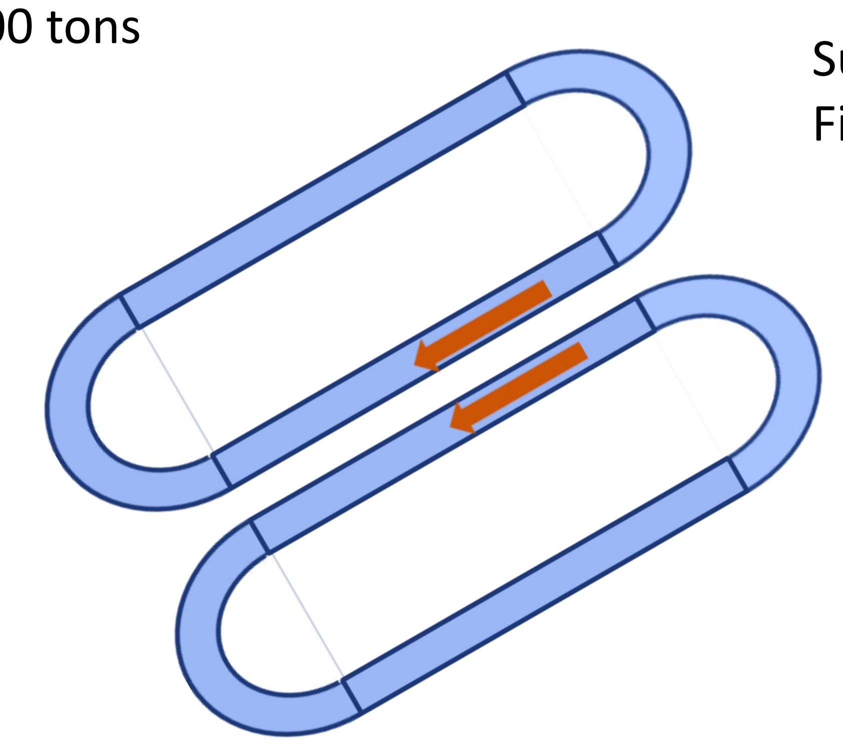
Concept design of LTS motor



Field coil assembly

- **The inner armature is rotational, and the outer SC field coil assembly is stationary. Pro: no need for a rotating cryogenic coupling. Con: brushes and collector rings to supply power to the armature**
- **Field coil assembly includes:**
  - 30 NbTi racetrack-shaped field coils. Peak field ~7 tesla
  - Field coil support structure
  - Thermal shield (aluminum), outer vacuum vessel (stainless steel)
  - Torque tubes (inner, outer): trade-off mechanical strength vs low losses
  - Cryogenic support:
    - MRI-proven minimum-cryogen *Freelium*™ technology: A closed-loop high reliability, low maintenance approach, does not require the liquid cryogen refills
- **Conventional (resistive) stator/armature albeit a different configuration**
- **Generator features:**
  - Generates over 2 T field in air gap vs ~1 T in conventional machinery
  - Simplified motor design due to large air gap: 10 - 15 mm vs 5 - 7 mm in conventional units
  - Higher efficiency ~99%
  - No need in ferromagnetic core ➔ factor of two weight reduction, lower forces
  - Field coils produce a dc magnetic field
    - Output power is controlled by changing ac current in the armature coils
    - Temporal and spatial harmonics from armature are small although not negligible
  - Total length of SC wire ~75 kAmp-km
  - Weight: ~100 tons

Superconducting Field coils



Comparison of SC machines for ship propulsion

	LTS Field Coil Assembly	AMSC HTS Field coils [1]	Homopolar Inductor Alternator, HTS [2]
Output Power (MW)	36.5	36.5	36
Speed (r/min)	120	120	120
Number of poles	30	16	18
Terminal voltage (kV)	6	6	3.8
Armature current (A)	3600	1270	
Efficiency (%)	99	**97**	>95
Mass (ton)	43	75	100
Length (m)	1.8	**3.4**	4
Outside diameter (m)	4.3	4.1	2.9
Armature cooling	Forced air	Liquid	

[1] B. Gamble et al -- *Full power test of a 36.5 MW HTS propulsion motor*, IEEE Trans. Appl. Supercond., (2011)
[2] K. Sivasubramaniam et al - *High power density HTS iron core machines for marine applications*, IEEE PES (2007)

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Quench protection

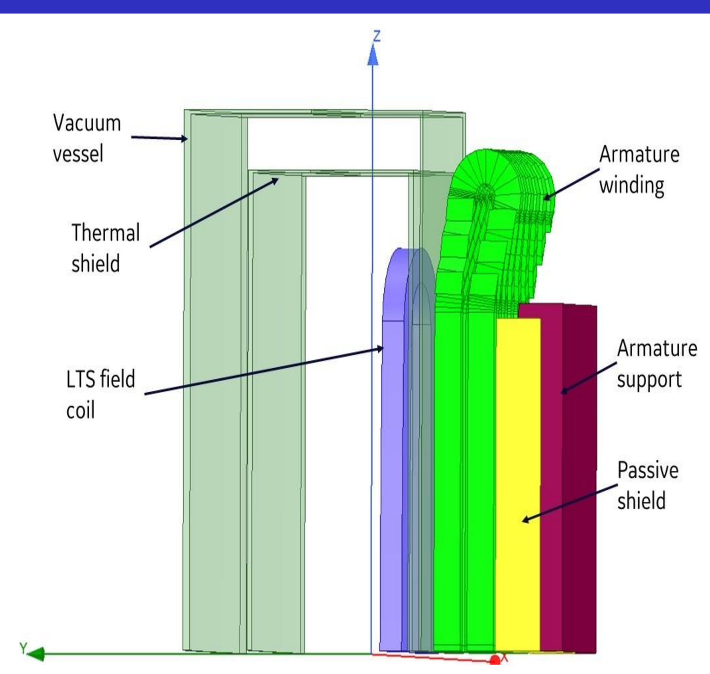
Challenges

- ➢ High stored energy in field coils
- ➢ High current density
- ➢ Multi-coil configuration
- ➢ Can not use an external resistor
  - ➔ Need factor of two current reduction in <3 sec

Approaches

- ➢ MRI-type quench protection: passive detection with internal protection
  - Con: need ~24 hours for operation to be restored
- ➢ Consider several series-connected or parallel-connected branches
- ➢ No-insulation approach to improve coil stability. Issues to address:
  - Shall not cause faulty activation of the protection system;
  - The current re-distribution in the coils shall not cause mechanical imbalances;
  - Shall not cause the coil damage or performance degradation.
  - Effect on the ramp time and field stabilization should be minimized.

Motor performance

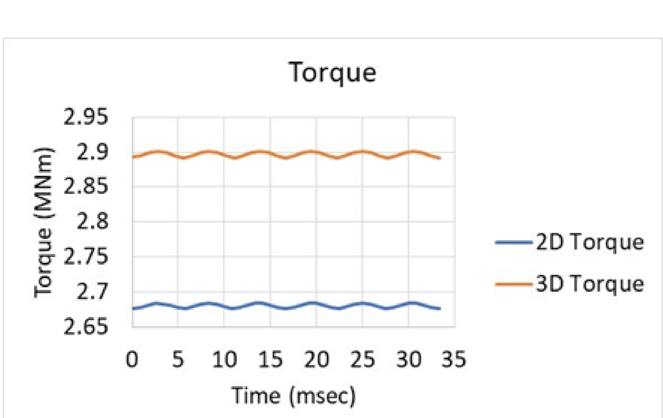


One pole EM model

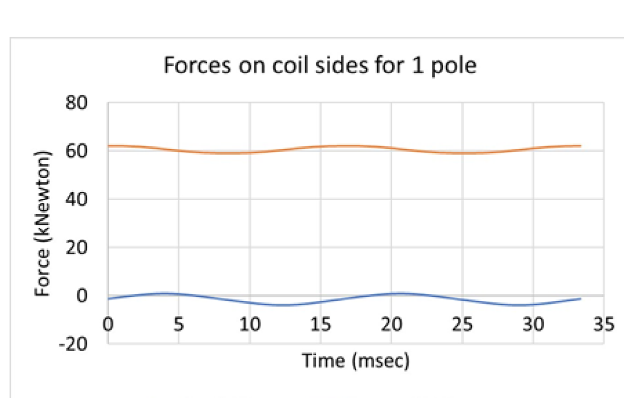
- ➢ **High-efficiency, low-loss configuration**
- ➢ **Major advantage of LTS approach: high field in the air gap of 2 tesla**
  - Typical HTS Demos: Peak field on conductor ~2 tesla. The air gap field:
    - o Up to 1.2 tesla (with heavy iron yoke)
    - o Less than 1 tesla without the yoke
- ➢ **The end turns contribute ~7% to the torque**
  - More efficient use of the active materials
  - Reduction of the coil length, lower motor weight
- ➢ **Small torque ripple of only 0.28%**
- ➢ **Non-magnetic teeth reduce the radial force**
  - The radial force is ~2.5% of the tangential force.
    - o Conventional machines: similar radial and tangential forces
  - Superconducting motor: an extremely low vibration and noise signature design is possible.

Losses at full load

Component	Loss (kW)
Armature copper loss	290
Magnetic shield loss	11
Armature support loss	0.04
Armature cooling	15
Slip ring loss	45
Cryocooler power	32
Vacuum vessel loss	0.036
Thermal shield loss	0.005



Small torque ripple
The 3D model includes 7% torque increase due to end-turn effect



Forces on coils
Reduced radial forces in the ironless motor

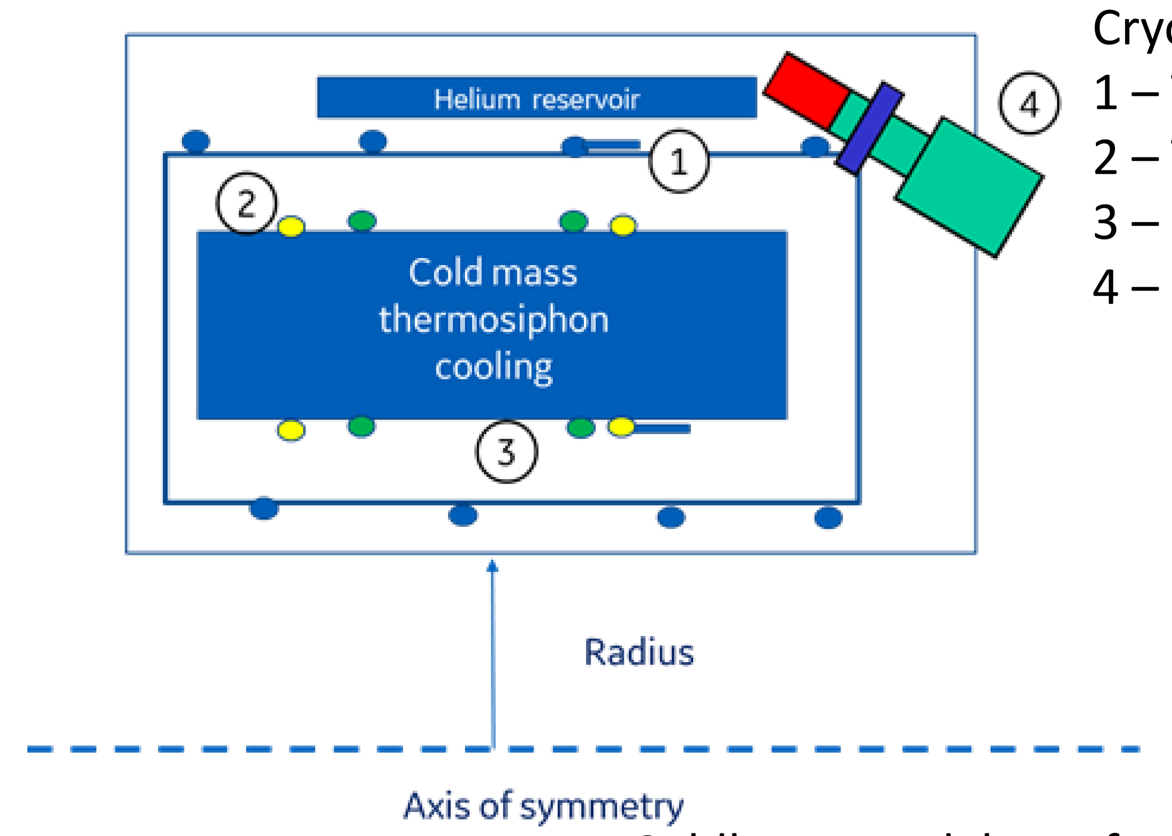
Cryogenic approach

Possible cryogenic configurations

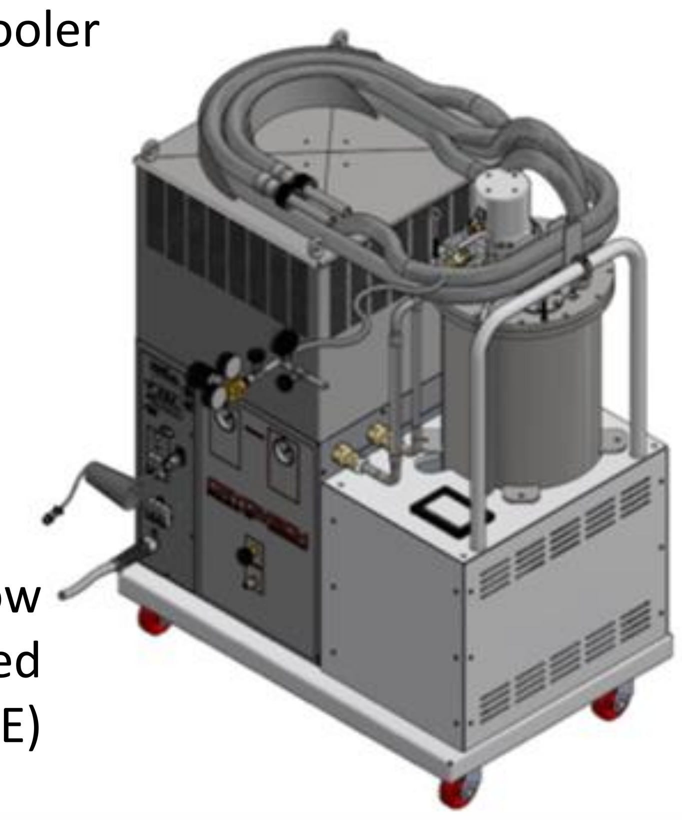
- ➢ **Immersing field coils in a cryogenic bath**
  - Mature, reliable: MRI experience
  - ZBO: unless quenched, most systems do not require He replenishment
  - Fast cool down, sufficient ride-through in case of power outage
  - **Cons:** Large LHe quantity (over 1,000 liters), LHe replenishment required after quench
- ➢ **Conduction cooling / Cryocooler, direct contact field coil cooling or use heat pipes**
  - Large number of cryocoolers
  - Long cool down, insufficient ride-through
  - Heavy
- ➢ **Forced-flow cooling (compressed, impeller driven)**
- ➢ **Thermo-siphon cooling**
  - Developed for MRI: GE *Freelium*™, Philips Blue Seal
  - Minimum LHe (~50 liters or even less)
  - Closed system: No LHe replenishment ever

Approach

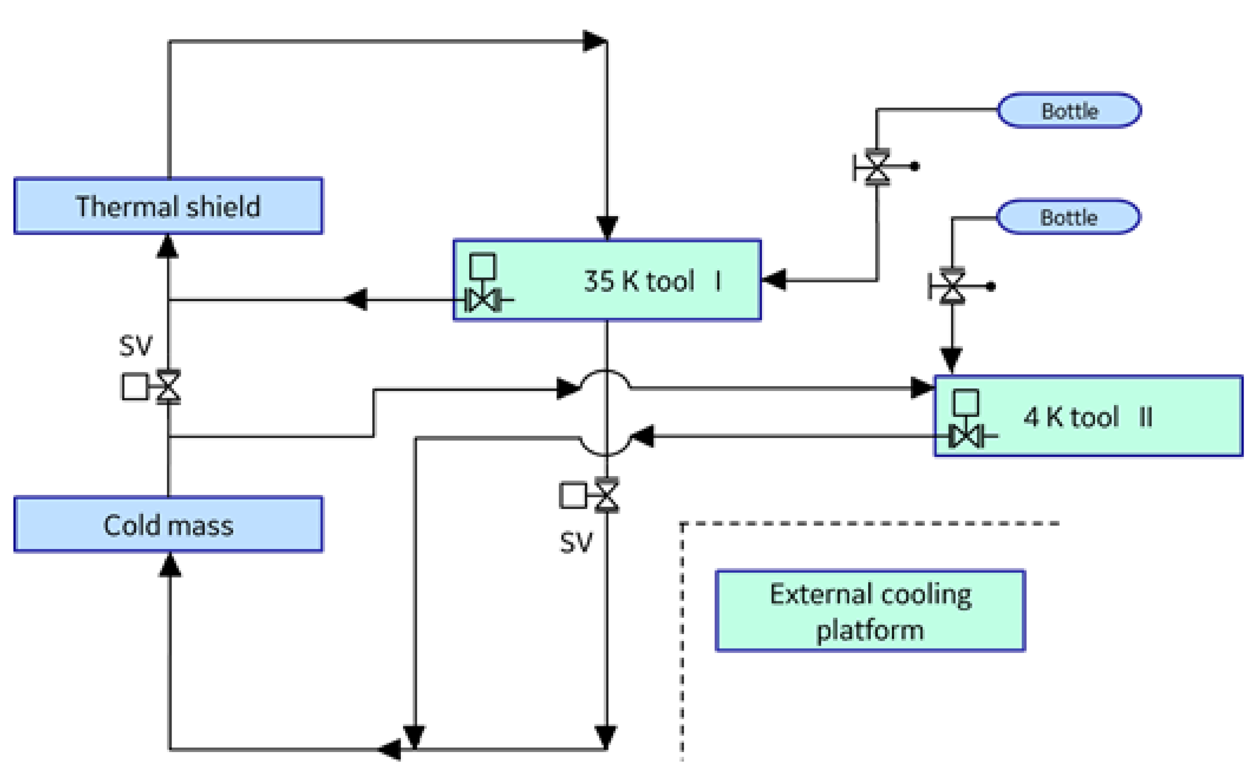
- ➢ **Combine forced-flow and thermo-siphon approaches**
  - Enables continuous operation during fault modes and in case of maintenance
  - Hermetically closed
  - ZBO cryogenic arrangement
  - Fast initial cooldown, steady state thermosiphon operation
  - Cryogenic maintenance and fault recovery using coldboxes on standby
  - Minimum idling power consumption



Cryogenic schematics and flow circuit
1 – Thermal shield
2 – Thermosiphon;
3 – Cold mass (field coils and coil former)
4 – Cryocooler



Coldbox: standalone, forced flow cryogenic tool circulating compressed helium (Cryomech/GE)



Helium flow schematics for service and backup

1. Initial cooldown for TS (1), cold mass (3),external, movable platform
2. Cooler maintenance, flow circuit (3), tool II
3. Re-cool, flow through circuit (3) and (1), tool I, (if (3) < 35 K, close SVs, evacuate tubes at (1), start tool II

Conclusion

A light weight, compact high efficiency, high power superconducting LTS 36.5 MW, 120 rpm ship propulsion motor is designed:

- **The inner armature is rotational, and the outer SC field coil assembly is stationary.**
- **Large air gap: 10 to 15 mm**
- **High field of 2T+ in air gap allows a compact, high-efficiency unit**
- **MRI-type quench protection**
- **A closed-loop cryogenic approach, does not require the liquid cryogen refills**
- **Total length of SC wire ~75 kAmp-km**
- **Weight: ~100 tons**