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Cooling topology options for HTS rotating electric machinery

Leslie Bromberg[1], Edward Chen[2], Philip C. Michael[1], Seungyong Hahn[3], John P. Voccio[1], and Haran Karmaker[2]

[1]MIT Plasma Science and Fusion Center, Cambridge, MA, USA

[2]TECO-Westinghouse Motor Company, Round Rock, TX, USA

[3]Applied Superconductivity Center, NHMFL, Tallahassee, FL, USA

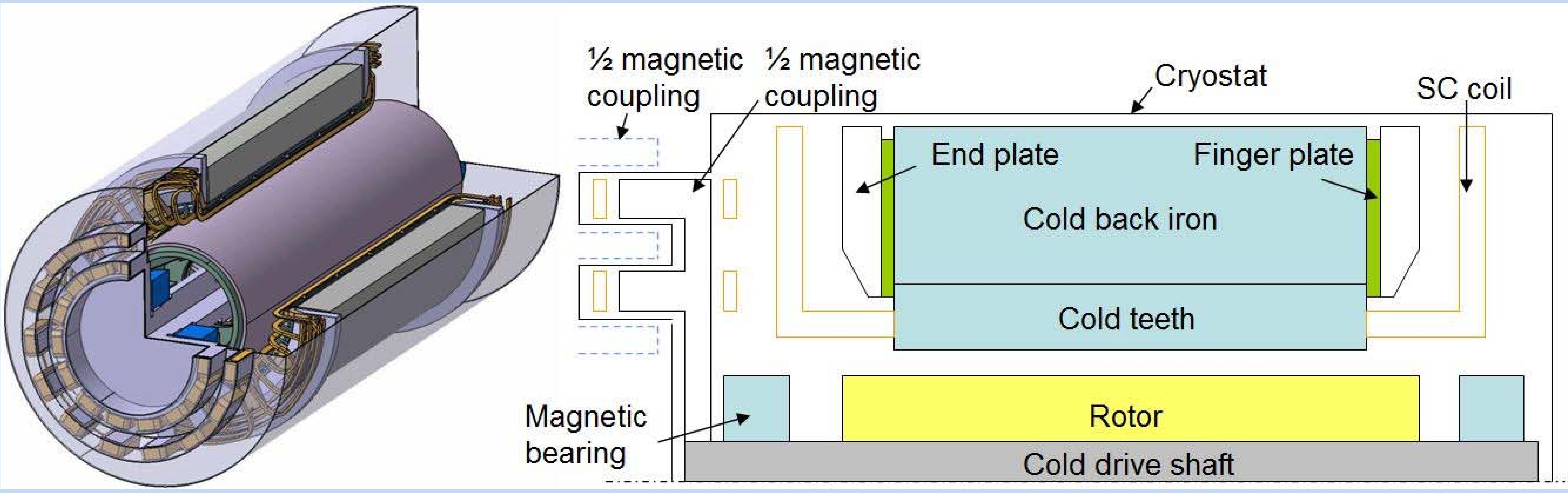
Motivation

- High-temperature-superconductors are being developed for use in rotating electric machinery
  - Rotors for low speed, medium power (5~10 MW) wind turbines
  - Fully-superconducting high-speed machines for airpower & shipboard generation and propulsion
- Challenging cryosystem design for high-speed, fully-superconducting machines
  - High AC losses in stator
  - Rotor cooling typically requires high-speed cryogen transfer coupling

Objective

- Examine unconventional cryostat configurations to reduce cryosystem demands
- Emphasize cooling options for high ac loss stator windings

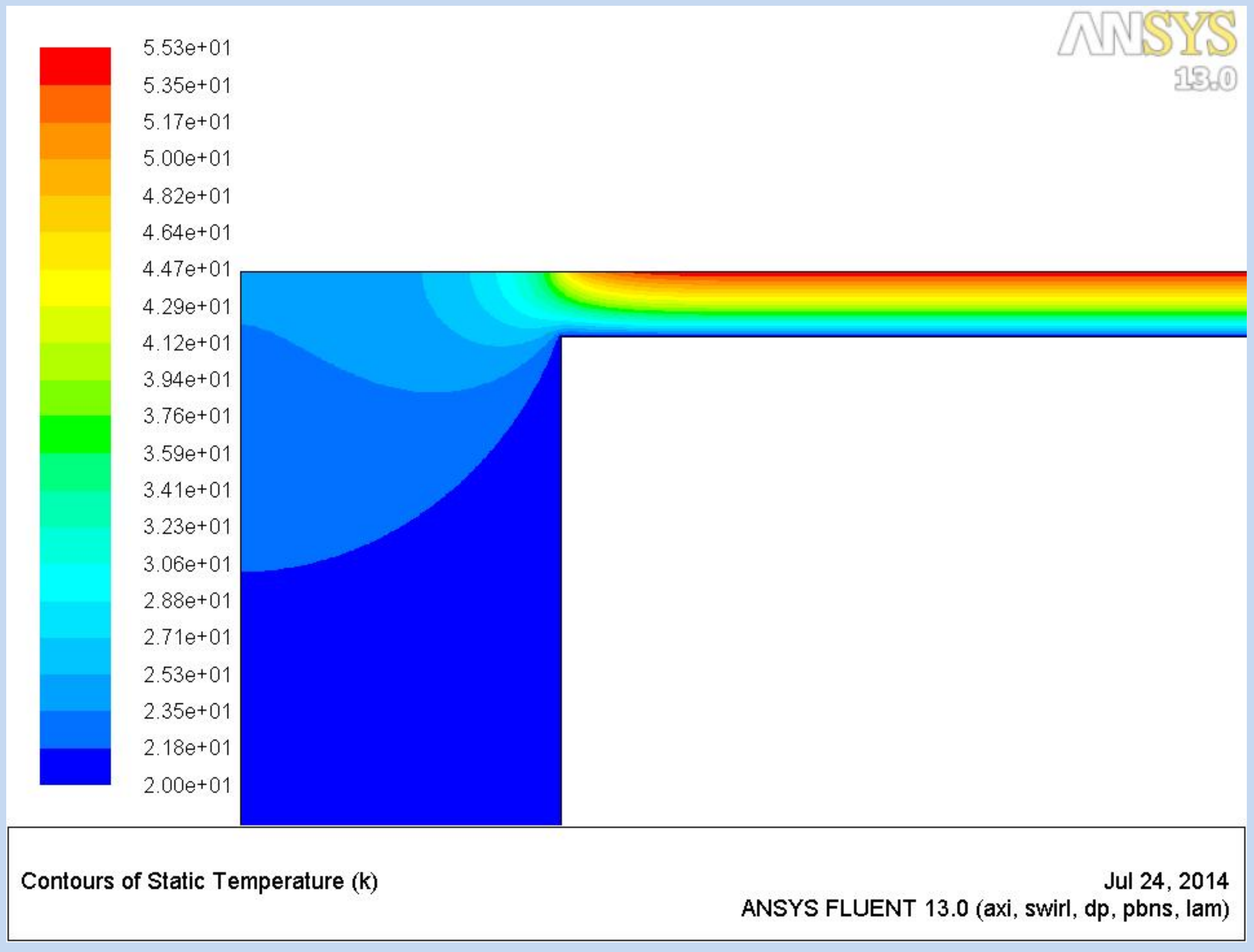
Common cryostat configuration



Feature	Pro	Con
Active 20 K cooling of MgB_2 stator, convection cooling of 50~60 K ReBCO rotor	√ Elimination of high-speed rotor cryocoupling	X Need to control cryostat residual gas pressure – balancing windage vs. heat transfer X High heat load from cold back iron
Torque transfer through magnetic coupling and non-conducting cryostat boundary	√ No hermetic shaft seals	X Large size, complex configuration, large cantilever for rated torque
Magnetic bearings inside cryostat	√ Large reduction in rotating friction heat load	X The load (motor weight and torque) gets transmitted through the cryostat. X Low radial stiffness may affect dynamic mechanical stability

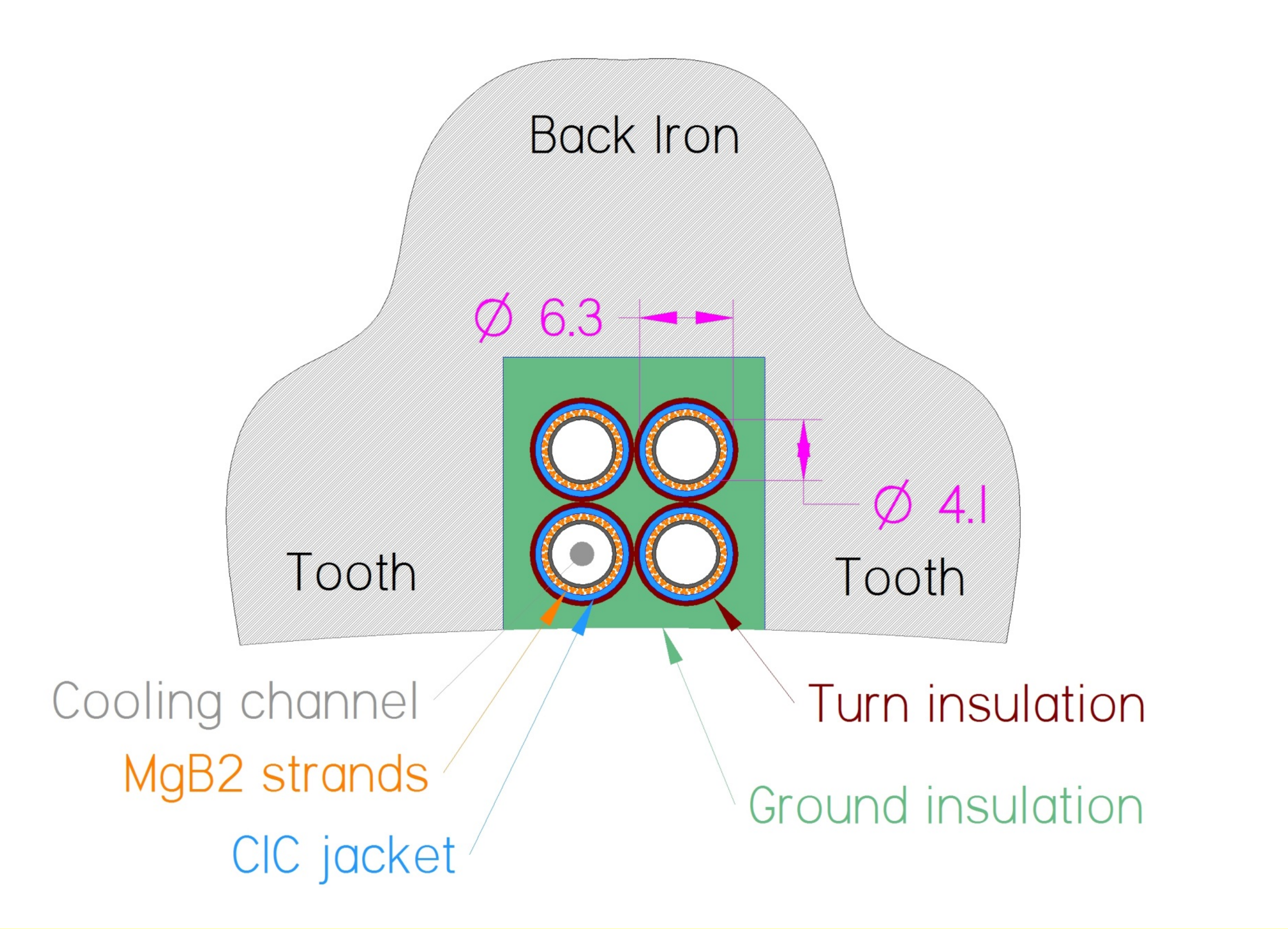
Residual gas cooling for ReBCO-based rotor

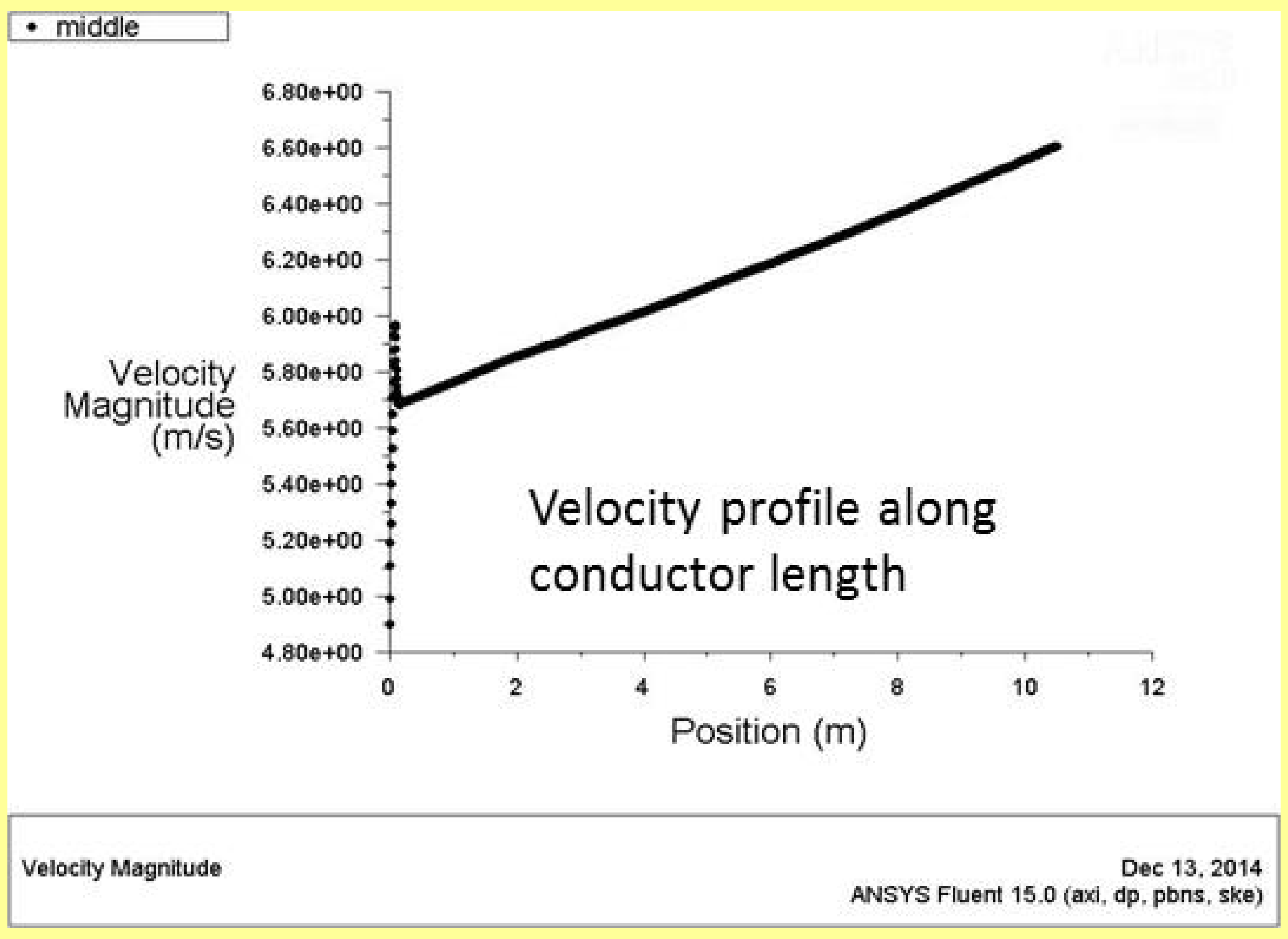
- Assume 1 m long, 0.36 m diameter rotor
- Allow a rotor heat load of 130 W (~100 W/m^2)
- Use ~1 mTorr H_2 or He gas pressure in cryostat for cooling where, conductivity, k, viscosity, υ, are pressure independent
- Actively cool stator to ~ 20 K
- Simulate operation at 7000 rpm, with 1 cm gap
- Roughly 35 K temperature difference stator to rotor
- 0.01 N-m torque and 10 W loss to windage



Stator conductor and cooling design

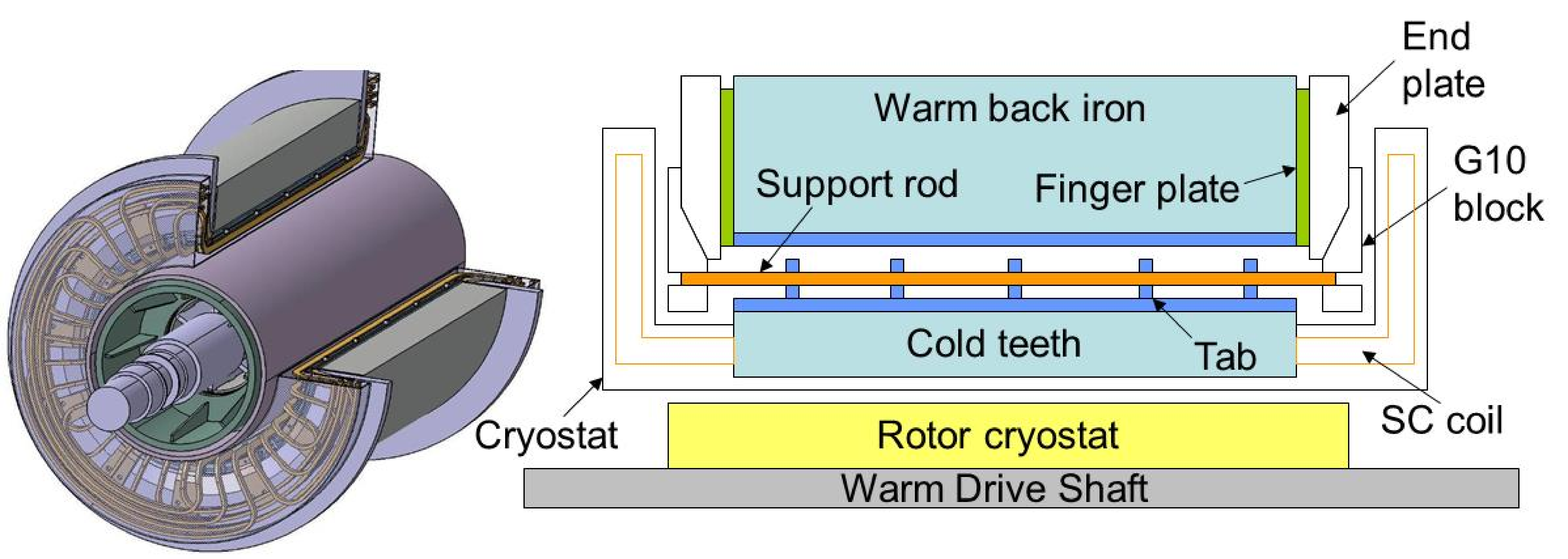
- Conductor based on fine-filament MgB_2 strand
  - ~10 μm filament diameter
  - ~10 mm twist pitch
  - ~ 10^{-6} Ohm-m matrix resistivity
- Two-channel cable-in-conduit configuration
  - Inner cooling channel diameter accommodates conductor ac losses (hysteresis, coupling, transport current)
  - 15~20 m conductor length per stator winding
  - Strand diameter and number to fit annular cable space
- Helium gas cooling
  - 20 K, 20 atm gas supplied at conductor inlet
  - ½ atm pressure drop, 3 K temperature rise at outlet
- Estimated stator losses for 14 MW, 7 krpm, 6.6 kV design
  - 1.7 ~ 3 W/m conductor ac loss
  - 1.0 ~ 1.5 W in iron teeth
  - 25~30 kW in back iron





Velocity profile along conductor length

Separate cryostat - for rotor, and entire stator



Feature	Pro	Con
Separation of teeth from back iron	√ Removes large back iron loss from cryogenic environment	X Complicated cryostat design and stator assembly
Use of non-magnetic teeth between stator windings	√ Removes iron tooth loss from cryogenic environment √ Provides robust mechanical support for stator windings	X Increases magnetic field amplitude (and hysteresis ac loss) on stator conductor
Use of conventional room temperature rotor bearings	√ Proven technology	X Challenging design to minimize heat leak to rotor while maintaining high shaft stiffness for dynamic stability

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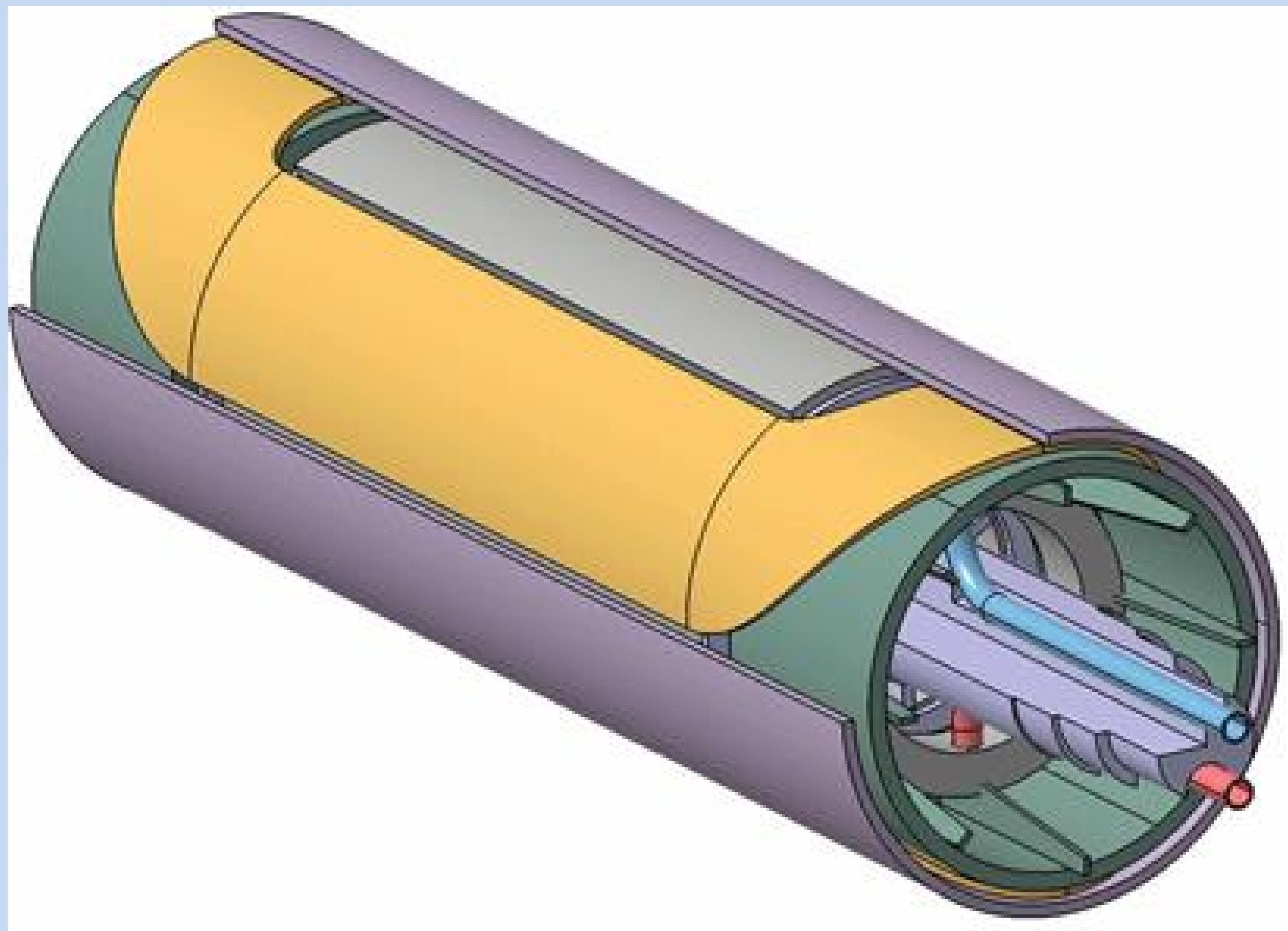
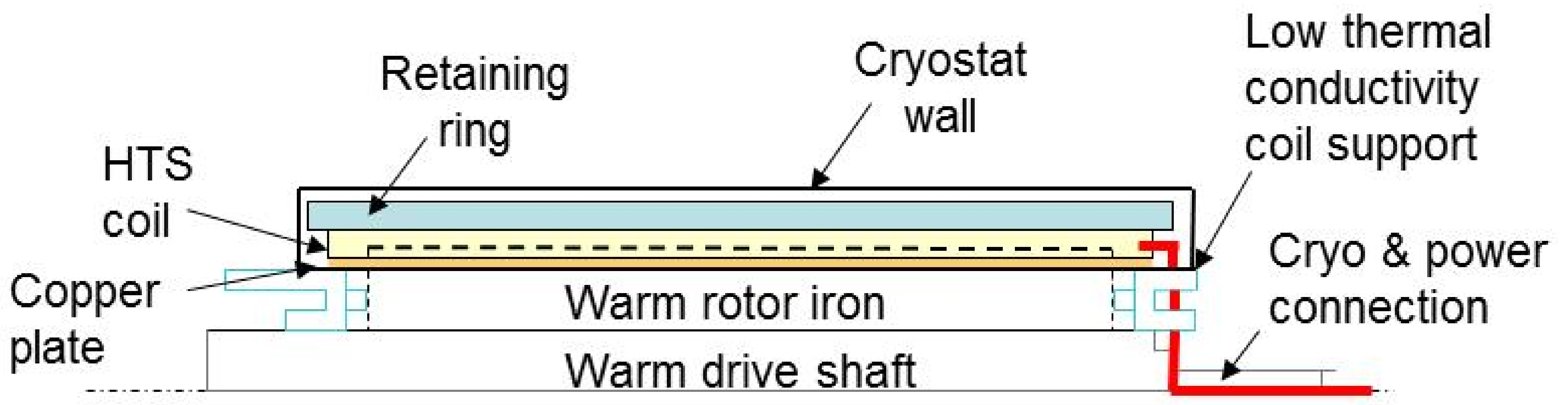
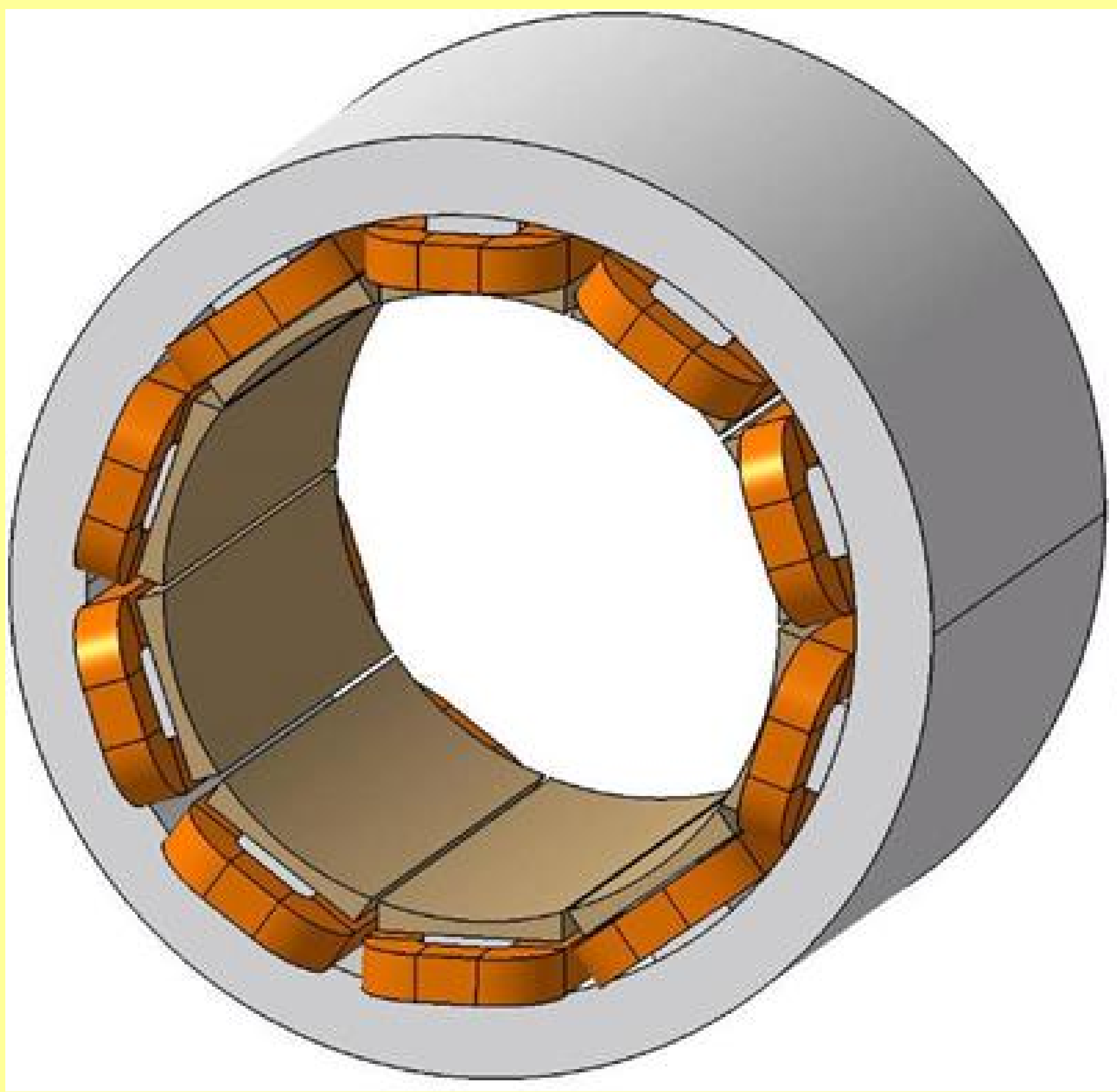
Rotor cryostat design considerations

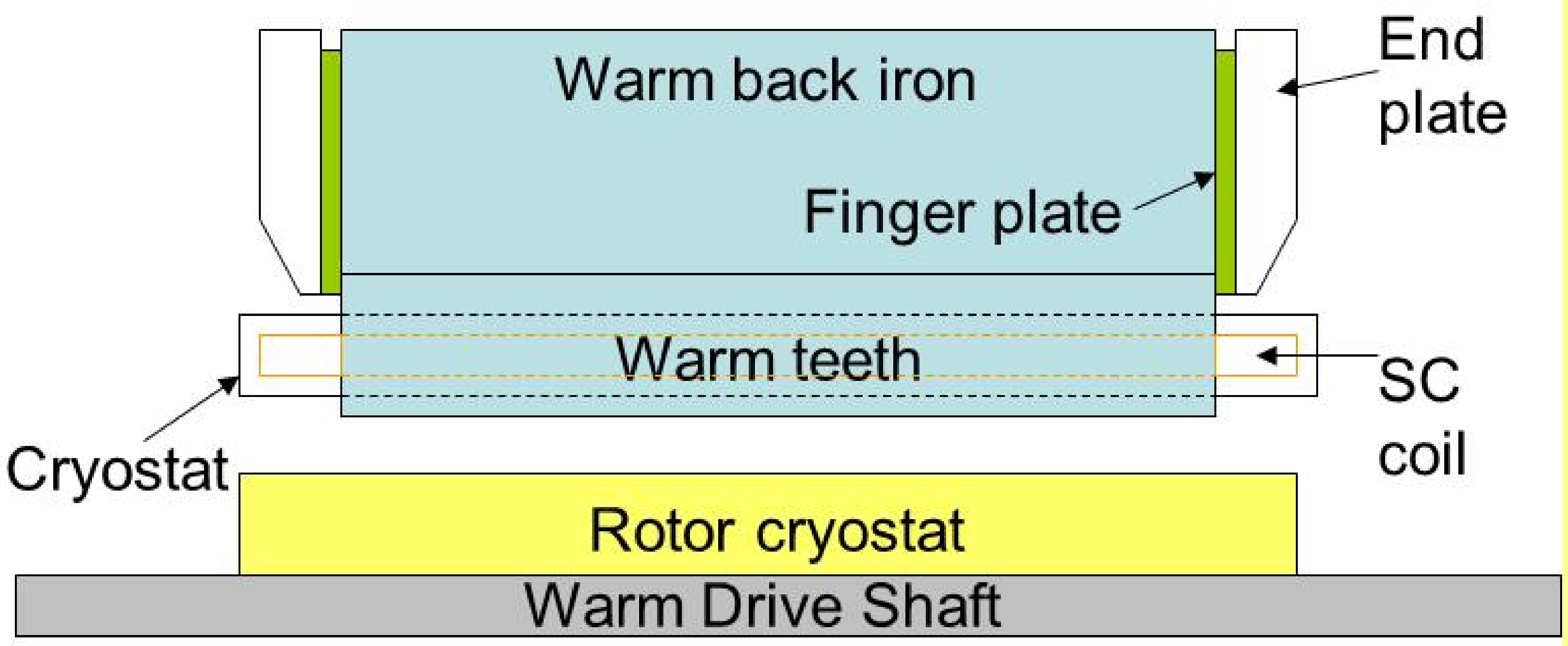




Feature	Pro	Con
Warm rotor iron	√ Faster cool down time	X Space constraint X Complicated cryostat design
Cryogenic transfer coupling	√ Increased cooling reliability compared to residual gas transfer	X Challenging design at this rotational speed

Stator with individual coil cryostats





Feature	Pro	Con
Elimination of cold stator iron and cold stator teeth	√ Significant reduction in cryogenic heat load	X Reduction in mechanical support for stator windings; Large number of load cycles (7 Billion/yr) may limit lifetime of internal cryostat structural/thermal elements
Introduction of cold bus between stator windings	√ Permits replacement of individual faulty coil	X Complicated assembly and QA procedures
Introduction of adjacent phase winding in common slots	√ Simplifies assembly √ Maximizes use of rotor field	X Leads to significant magnetic field peaking X Cryostat design significantly limited by the space constraint between the teeth

Summary

- Significant challenges to the development of high-speed, HTS rotating electric machinery exist
  - Relatively high conductor ac loss, compared to equivalent LTS conductors
  - Carnot efficiency gain from higher temperature (20~50 K) gas cooling, offset by low coolant density
  - Use of high-speed cryo-transfer coupling for rotor cooling remains challenging
- Additional cryostat topologies will be examined in effort to improve feasibility
  - No significant break throughs yet
  - Working to reduce magnetic field peaking for individual stator winding cryostat configurations