Cryogenic aspects of a 20 MW class Superconducting generator for the Renewables industry

W. Stautner[1], D. Torrey[2], M. Xu[1], A. Wu[1], M. Parizh[1], V. Soni[1]

[1] GE Research Healthcare, Electromagnetics and Superconductivity, Niskayuna, NY, 12309, USA
[2] GE Research Vernova, GE VR Technology, Niskayuna, NY, 12309, USA

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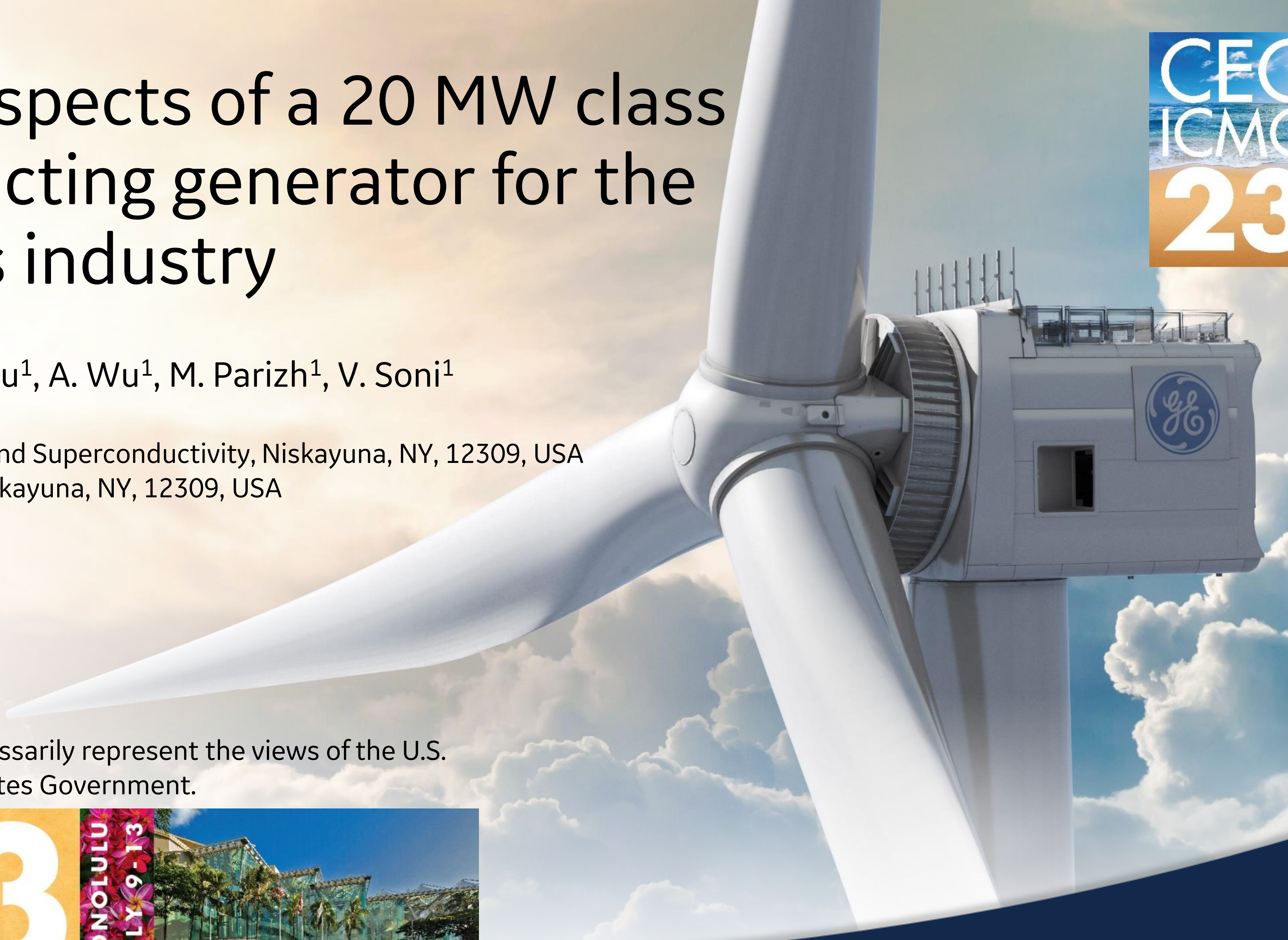

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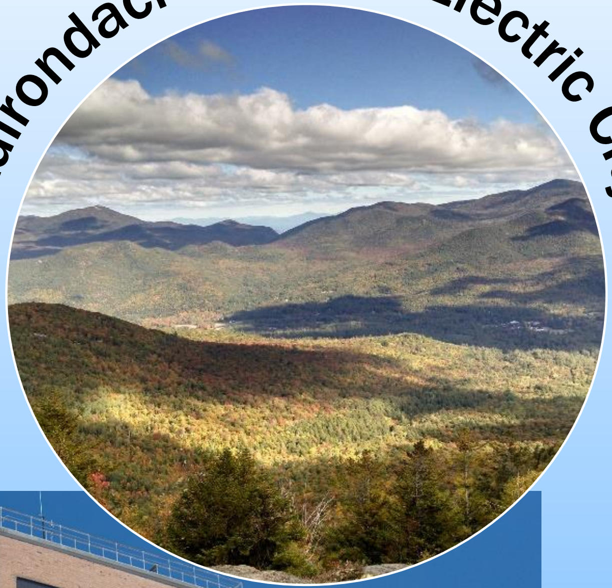

GE Research
1 Research Circle
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SC Generator – The Fine Print

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SC Generator - Agenda

SC Generator Cryogenics:

- Short Intro

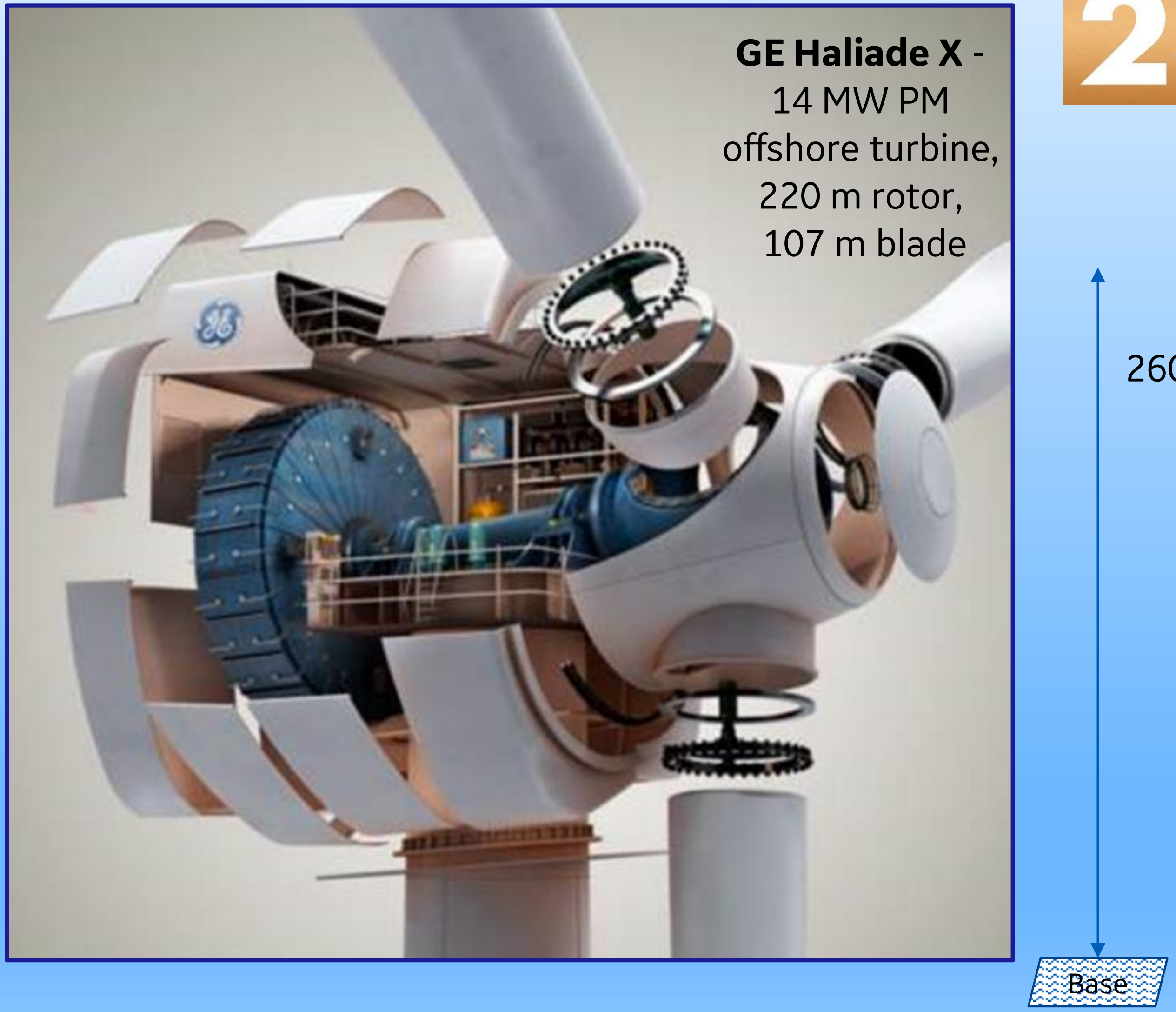
Cryogenic Challenges:

- Cryogenic system integration
- Thermal budget
- Cooling tube routing
- Coldbox with cryocoolers & maintenance
- Thermal shield / busbars (cold plates)
- Gas tanks
- Torque tube

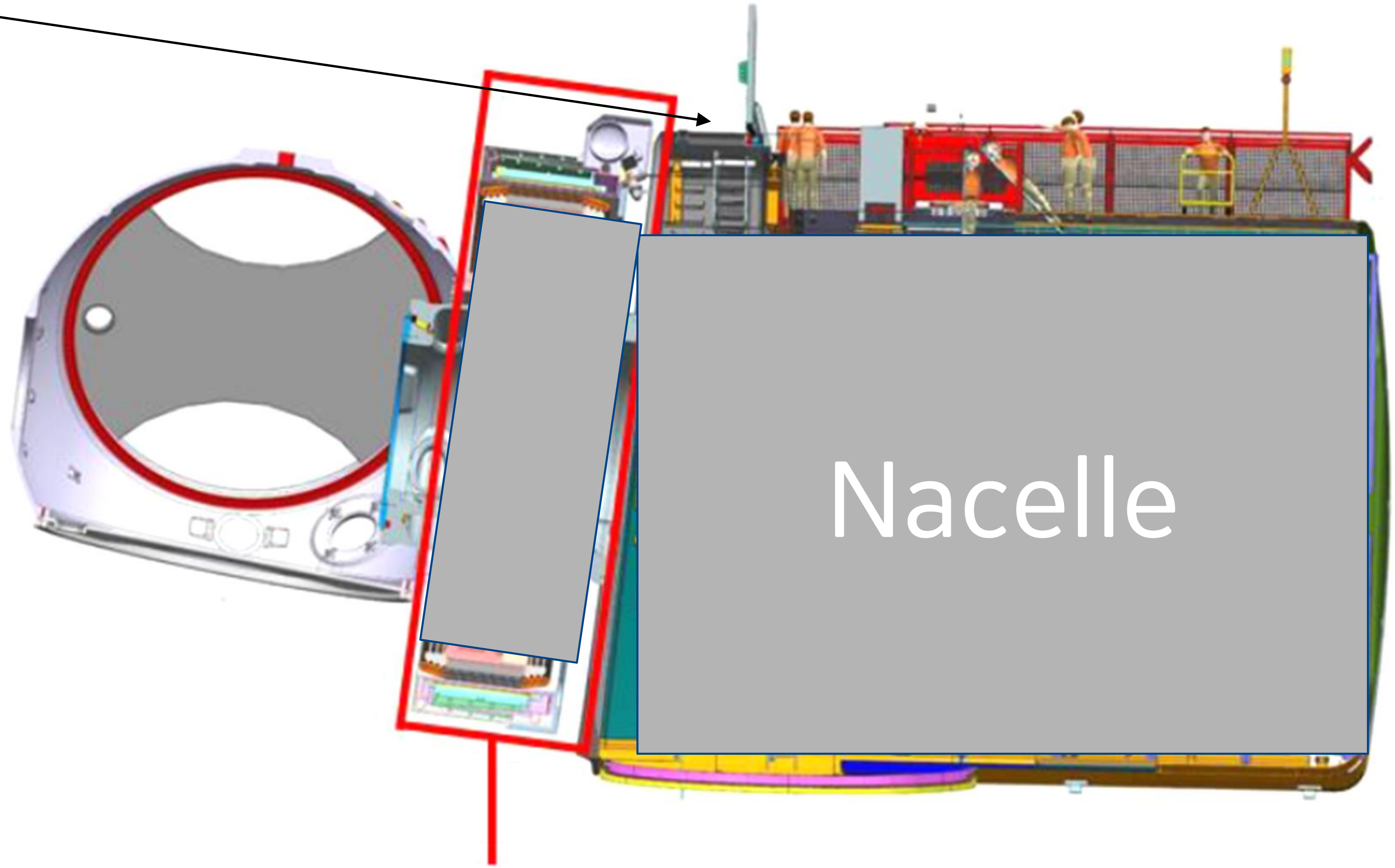
Summary and Conclusions

Background

- **Objective:**
  Reduce Levelized Cost of Energy (LCOE), slashing CO_2, eliminate use of rare earth PM and derived environmental hazards
- **Advantages** of SC Wind Generators and rotating machinery
  - **Higher field in air gap** vs traditional units
  - Scalability to higher power
  - Higher efficiency
  - Reduced size/weight of generator and turbine
  - Eliminates rare earth elements (if LTS is used)
- **Commercially-competitive Offshore units:**
  > 15 MW power
  - LTS offers an opportunity to commercially-competitive units
- **DoE Award:**
  GE to build a Prototype LTS Offshore wind generator



Cryogenic nacelle, housing compressors, chillers and access to cryocoolers



17 MW Generator located in Haliade-X Nacelle

SC generator – Drive Train and MRI Cryogenics

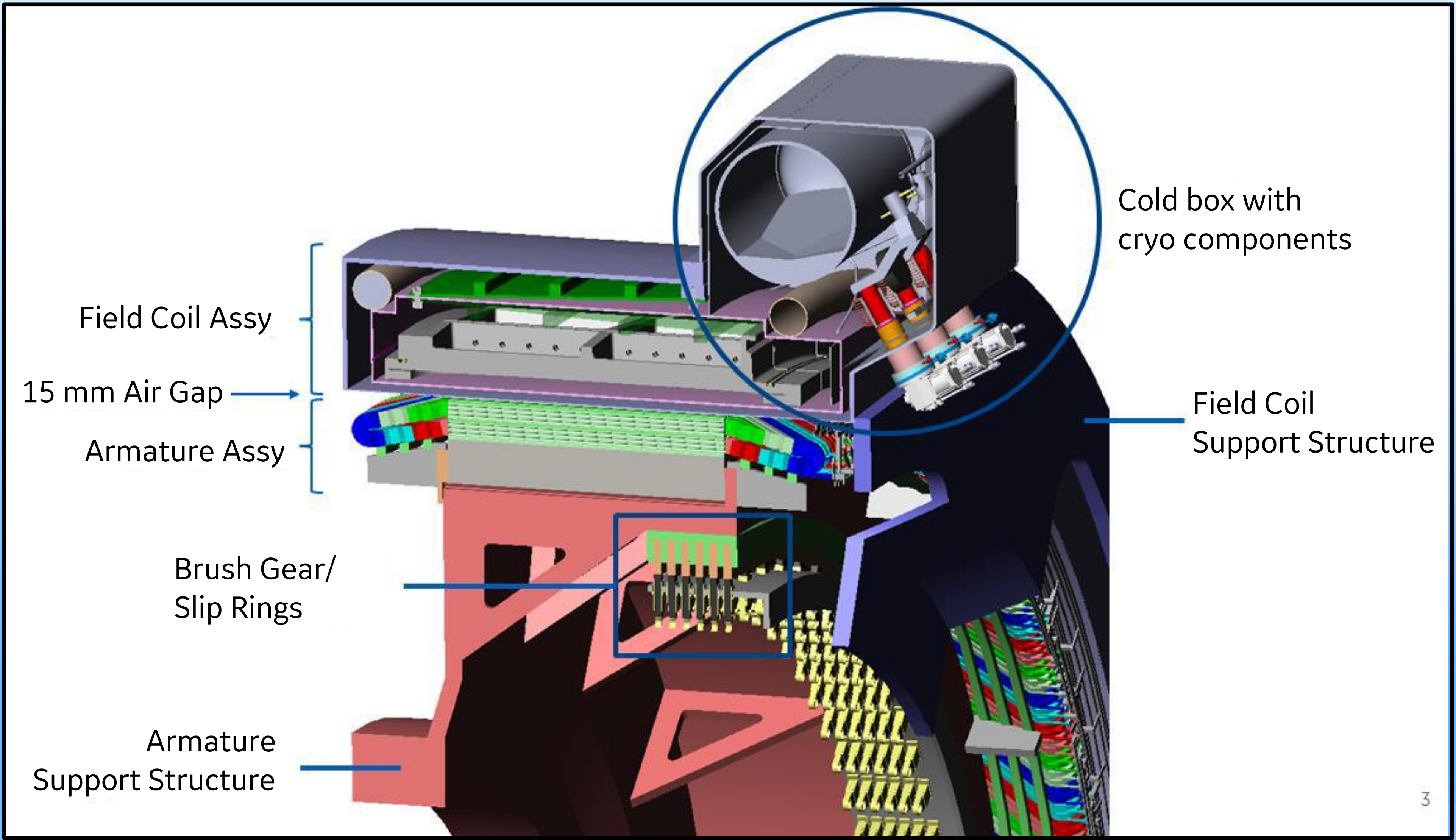
LTS environment

- 17 MW SC Generator with same space envelope as a 14 MW permanent magnet generator (PMG) for the Haliade-X turbine, with minor modifications of the nacelle
- Direct drive generator (DDG)
- Static Field coils (conventionally on the “rotor”), rotating Armature (conventionally on the “stator”)
- Superconducting Field coils are located outside of the conventional (resistive) Armature coils
- Air-core armature winding, forced-air cooled
- Field coils utilize low-temperature superconductor (LTS) copper-stabilized NbTi conductor routinely used in commercial MRI scanners
- Significantly higher magnetic field in the air gap vs conventional PMGs

Liquid helium environment

- *Freelium*™ closed-loop cryogenic system: GE technology proven in MRI scanners, minimum liquid helium (approximately 100 liters), no helium refill required, hermetically sealed
- To reduce schedule and expedite NPI, multiple generator components utilize technologies proven in volume-production MRI. At the same time, the SC generator will utilize many advanced materials and technologies to ensure customer benefits
- Complexity of structure results in severe challenges that need to be overcome, as we shall see

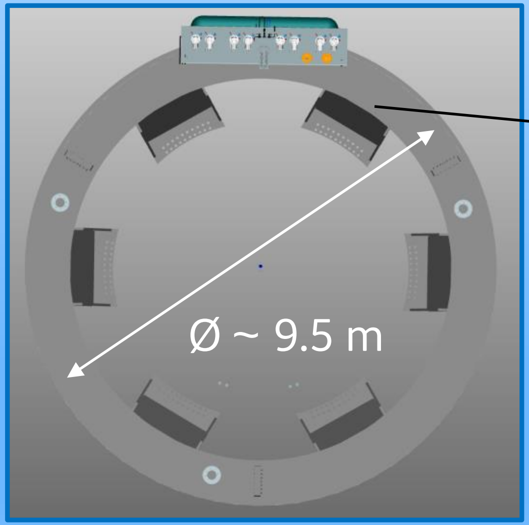
Cryogenic system integration

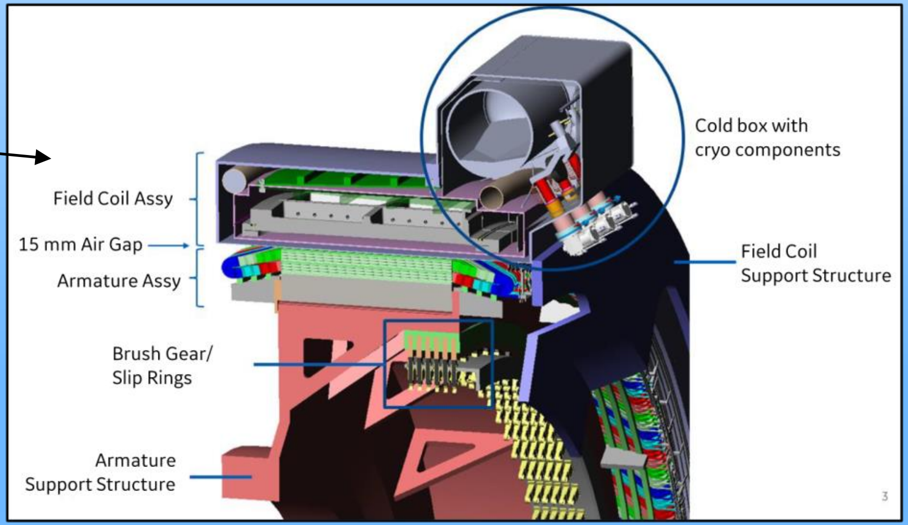


Some Design Parameters

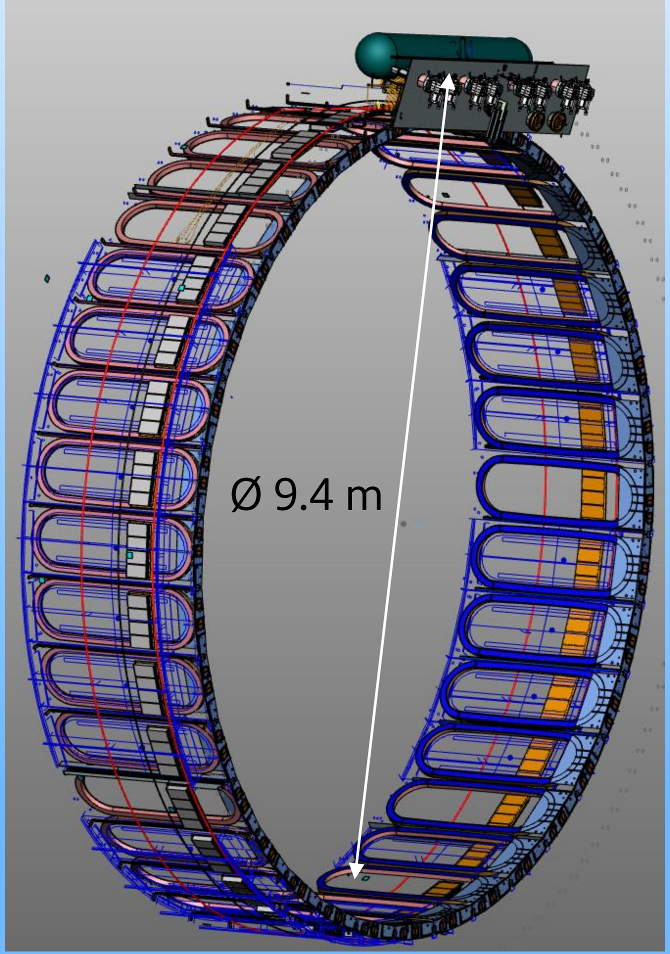
Generator	Design
Rated power	17 MW
Rated speed	8 rpm
Full Load Efficiency	97%
Air gap nominal	15 mm
Max maintenance downtime	12 hours/year
Mean time between maintenance	≥18 months

Field coils (outer)	Design
Conductor type	NbTi in copper matrix
Conductor length/coil	6.5 km
SC wire weight	3500 kg
Current density	260 Amp/mm^2
Amp-turns per coil	807 kAmp-turns
Peak field on conductor	6.8 Tesla
Total coil length	1,802 mm

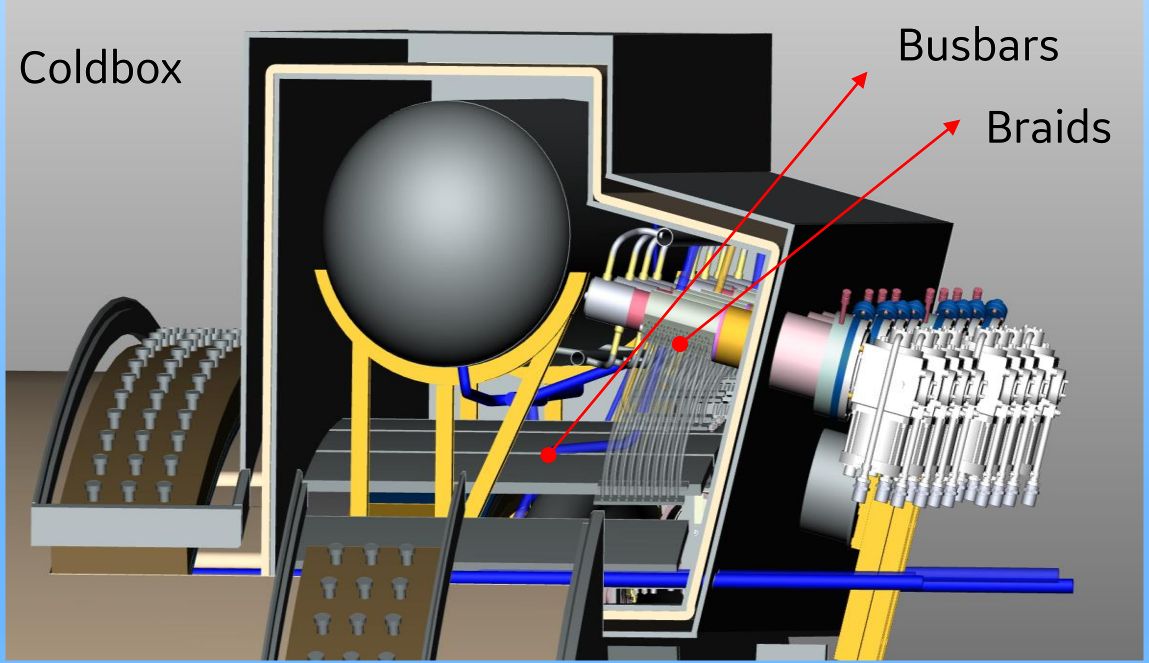




SC generator – Cryogenic Challenges (I)



- Stationary field coils allow us to implement thermosiphon technology
- Coldbox on top



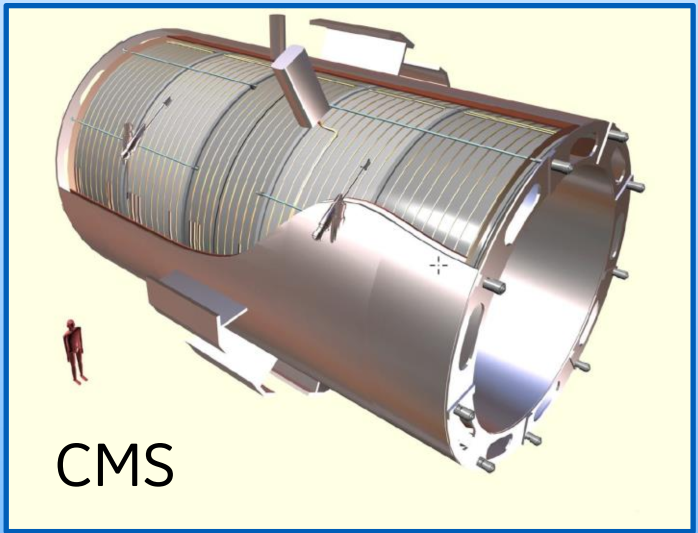
SC generator – Cryogenic Challenges (I)

Field coil cooling (thermosiphon tube routing)

- **NextGen MRI magnet systems** all work with thermosiphon technology developed over a period of 20 years[1]. Upscaled technology from 1.8 m to 9.4 m for SC generator.

- The technology to design and operate thermosiphons is known to work reliably since many years (early 70ies) and is currently in use or has been continually used in superconducting accelerator system designs (e.g. LHC/CMS, GEM detector magnets or others) for similar field coil former dimensions, within the 10 m diameter range (**7.5 m for LHC / CMS and 19.5 m for the GEM detector magnet**)[2].

- The main difference to our system is the low helium circulation loop for the thermosiphon (small 4 K heat flux density to drive the siphon).



Low vapor quality as compared to Compact Muon Solenoid (CMS)

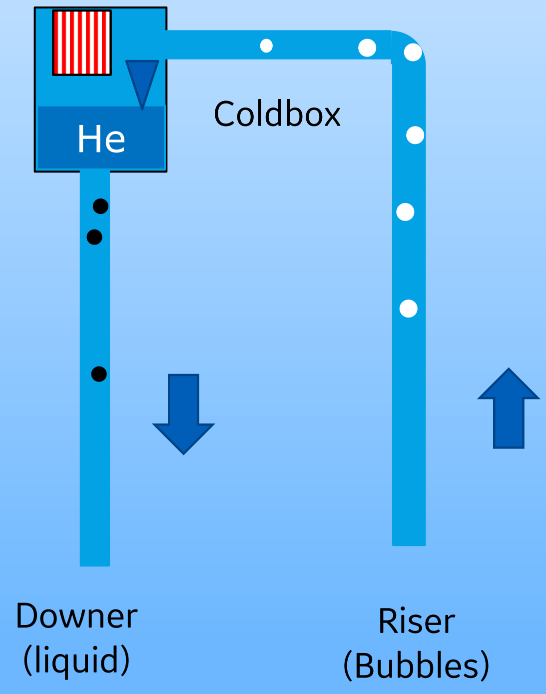
See also: [1] **MRI Magnets" in Handbook of Superconductivity,** M. Parizh, W. Stautner, Taylor and Francis, 2022

[2] **The liquid helium thermosyphon for the GEM detector magnet**, R. P. Warren, SuperCollider 5, pp 683-685, LLNL, 1993 and **CMS Coil Design and Assembly**, F. Kircher, P. Brédy, D. Campi, P. Fabbricatore, S. Farinon, H. Gerwig, A. Hervé, I.L. Horvath, B. Levesy, R. Musenich, Y. Pabot, A. Payn and L. Veillet, IEEE Transactions on Applied Superconductivity, vol. 12, Issue 1, 395-398, 2002

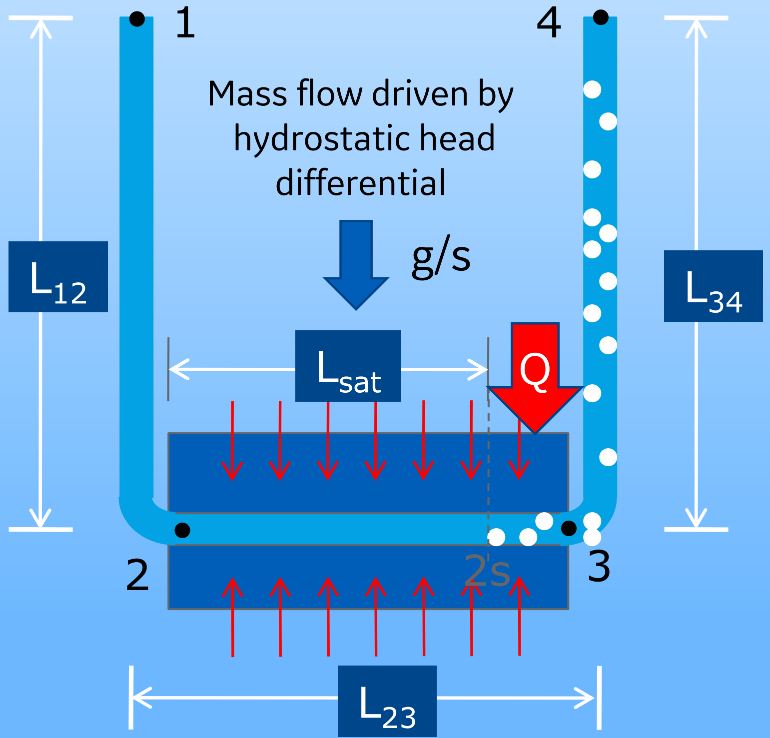
SC generator – Cryogenic Challenges (I)

- SC generator comes with a very small heat load to a 4 K environment, this means, the thermosiphon basically runs only in a kind of “conduction-cooled” mode

$$\Delta P_h = g(\rho_{12} - \rho_{34})L_{12}$$

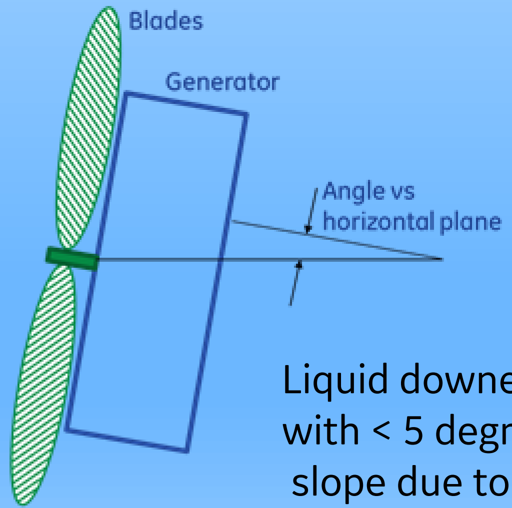


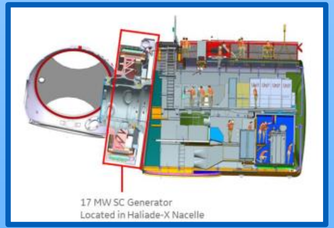
Upper part of siphon loop to coldbox



Lower part of siphon loop around coils

- *Caveat*: need to ensure there is always a slope built in into the cooling loop design
- All loops with slope toward recondensing units





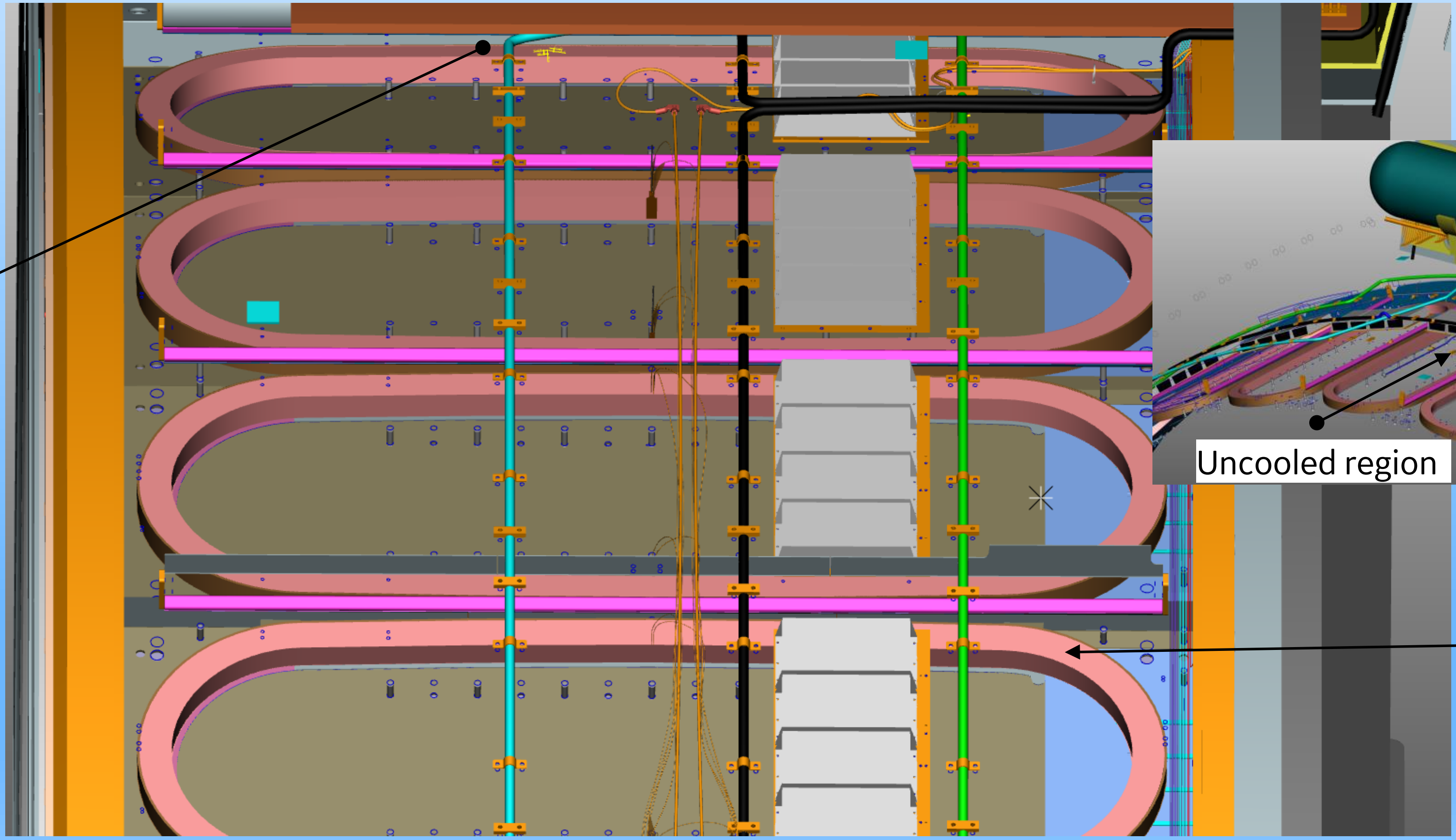
Liquid downer line to coldbox with < 5 degree allowable slope due to nacelle tilt angle

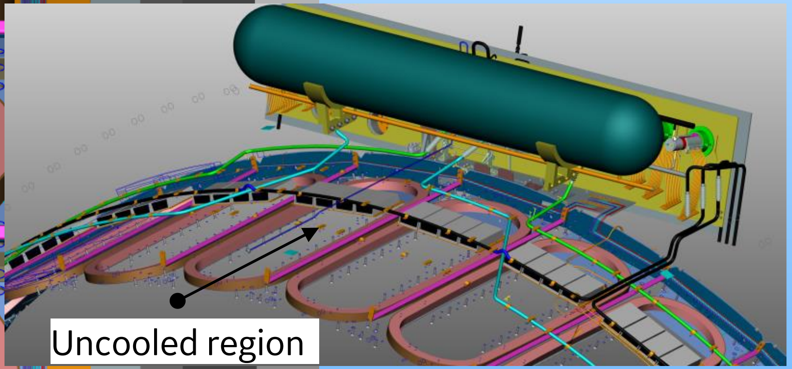
See also: **The Tubular Thermosyphon**, G.S.H. Lock, 1992 Oxford University Press

SC generator –Coil cooling / precooling

- Racetrack coils with cooling tubes embedded in the aluminum coil support structure
- Downer and riser tubes, chasing structural hot spots not cooled with cooling tubes
- Precool tubes connected to a cryoplant for initial cooldown, beware of tube shrinkage

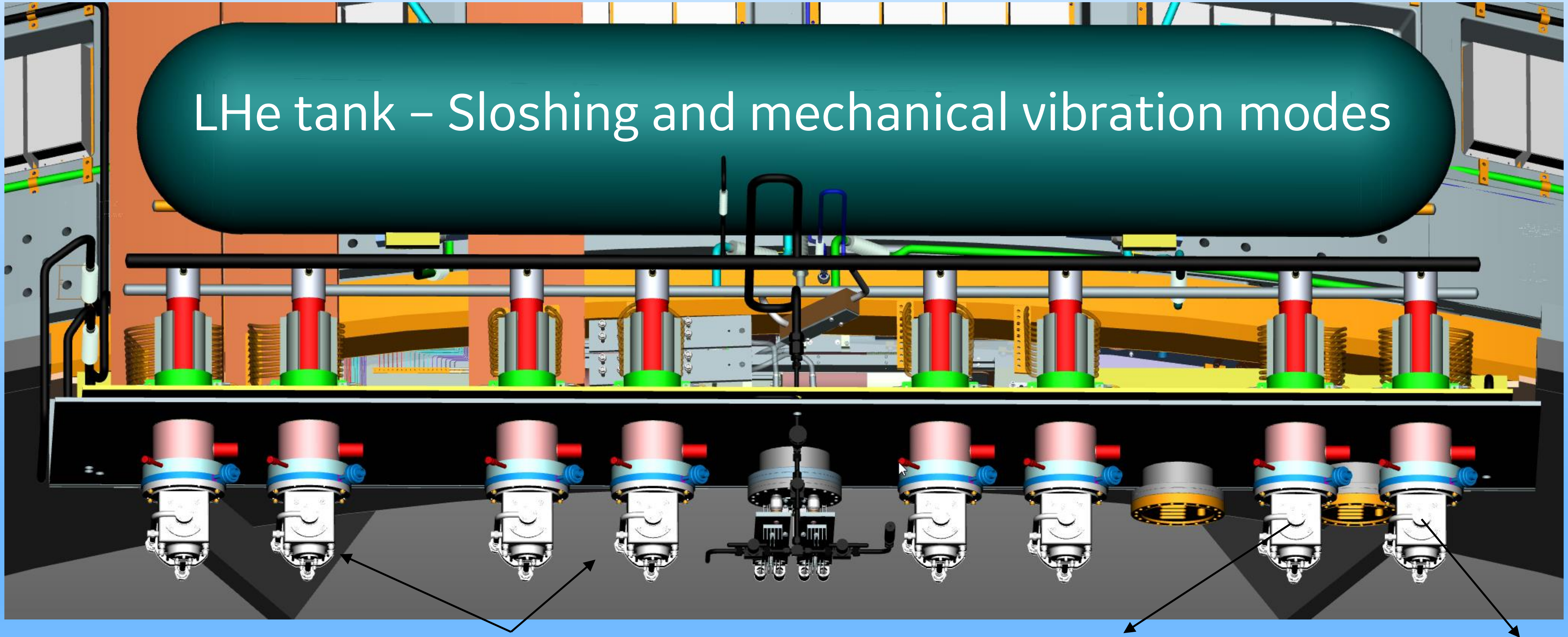
Need to direct the flow to the coldbox which leaves part of the top coils without direct cooling at the 12 o'clock position





SC generator – Cryogenic Challenges (II)

- Coldbox with cryocoolers in confined, minimized space
- High pressure liquid helium tank, low pressure during operation – thermomechanical effects in tubing
- Optimize manifold to ensure all coolers liquefy equally – 8 condensers with feed and return



6 SHI 412 RDE A4s for steady state operational mode

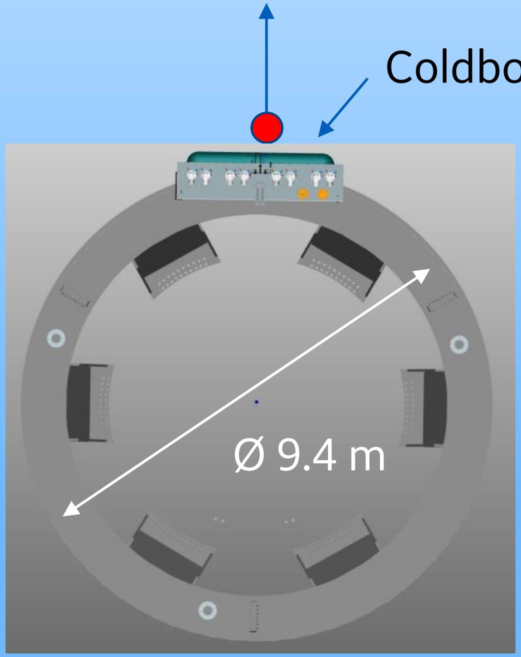
2 on standby and for thermal transients/maintenance

SC generator – Cryogenic Challenges (III)

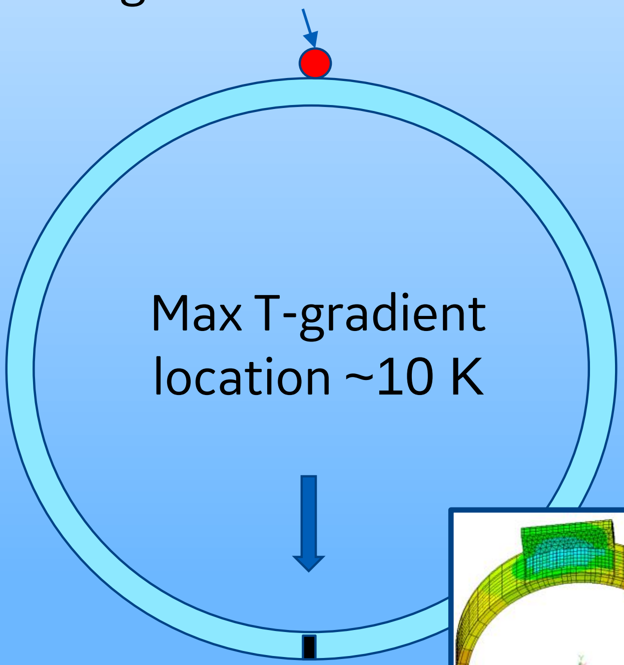
- Thermal shield needs to provide a uniform temperature enclosing the 4 K field coils
- Thermal shield basically conduction cooled, no thermosiphon

Top level conduction cooling path only

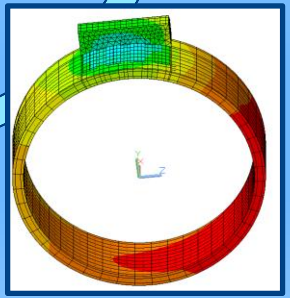
Coldbox

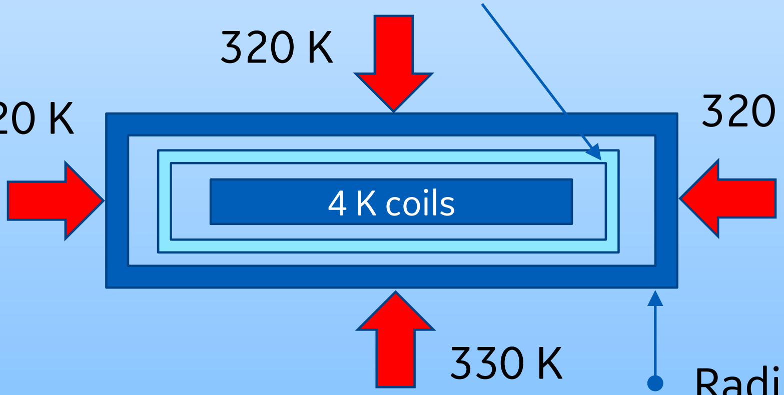


How to conductively cool a large thermal shield?



Thermal path length from top: 15 m

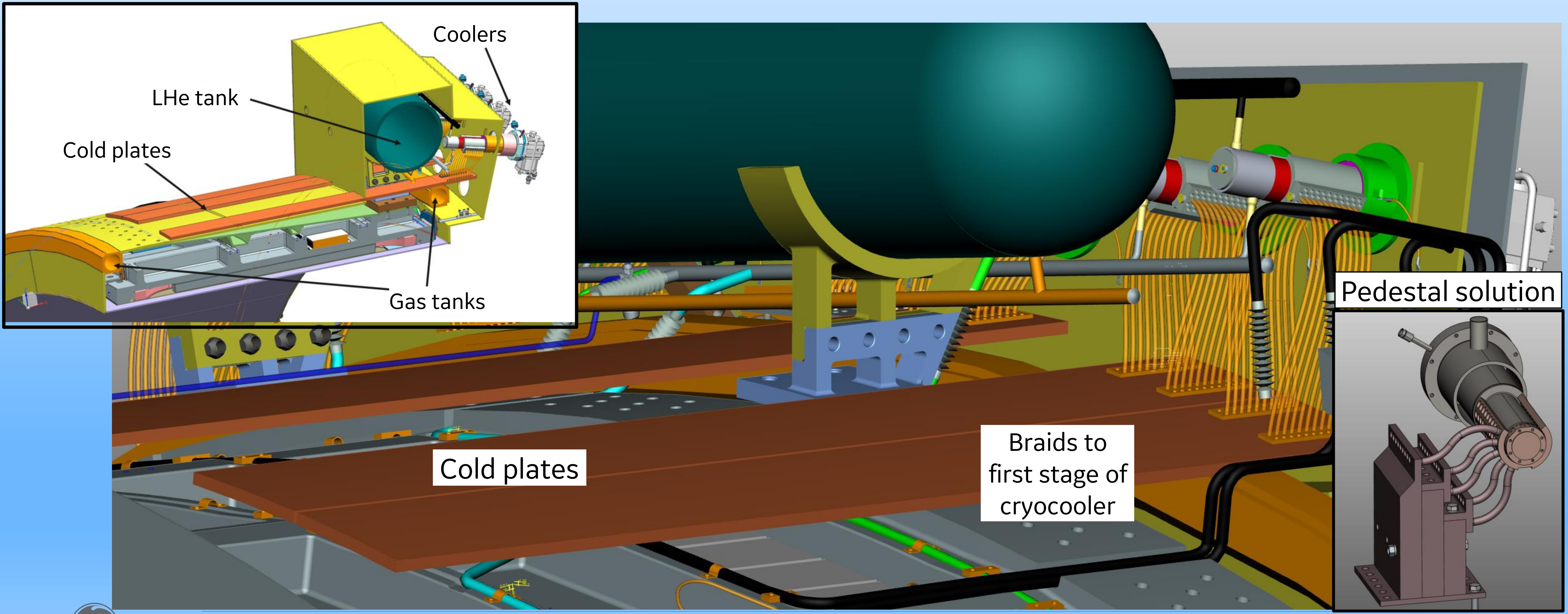




- Optimize thermal path circumferentially and axially
- Top TS needs need large surface area to be able to extract heat
- Thick-walled TS
- Use highly conducting material
- Make use of convective flow in buffer tanks for smoothening out T-gradients

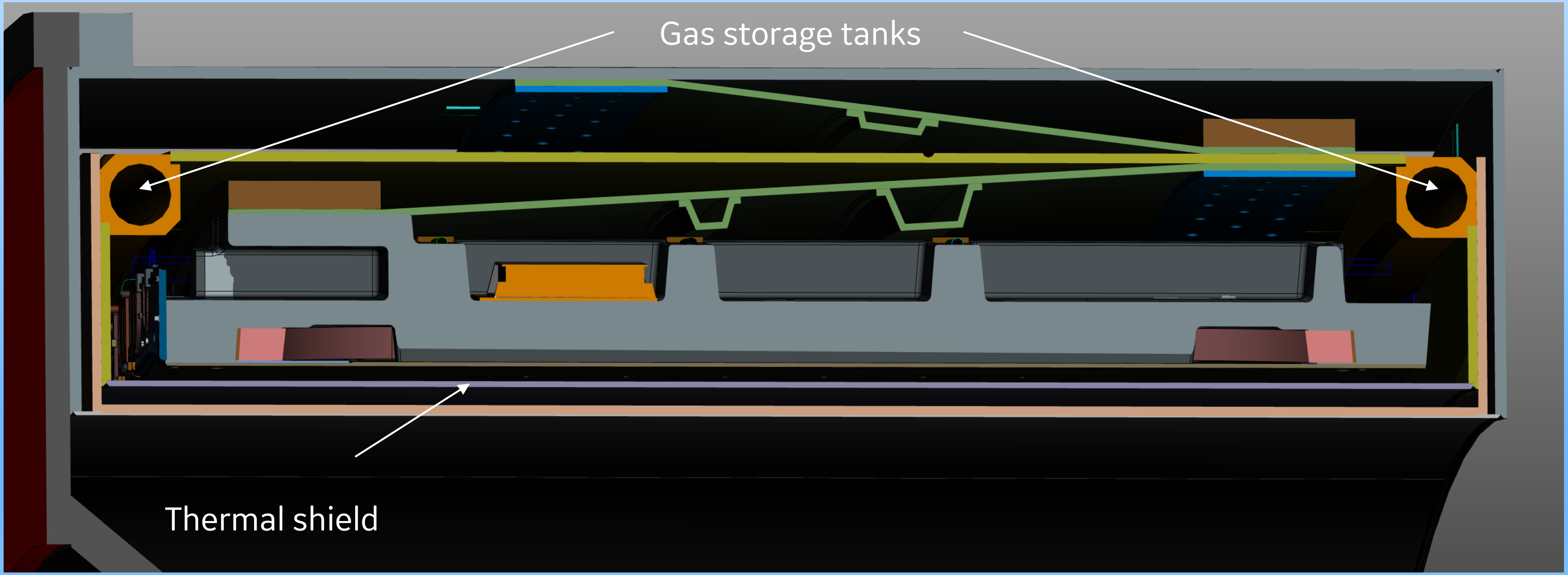
Thermal shield thermal bus/cryocooler links

- Large sized copper heat bus from thermal cryocooler braids to thermal shield top area
- Note that the braids are far too long, high dT, and need a pedestal solution for short braids or bend up 1 inch thick cold plate at cooler end (heat bus)



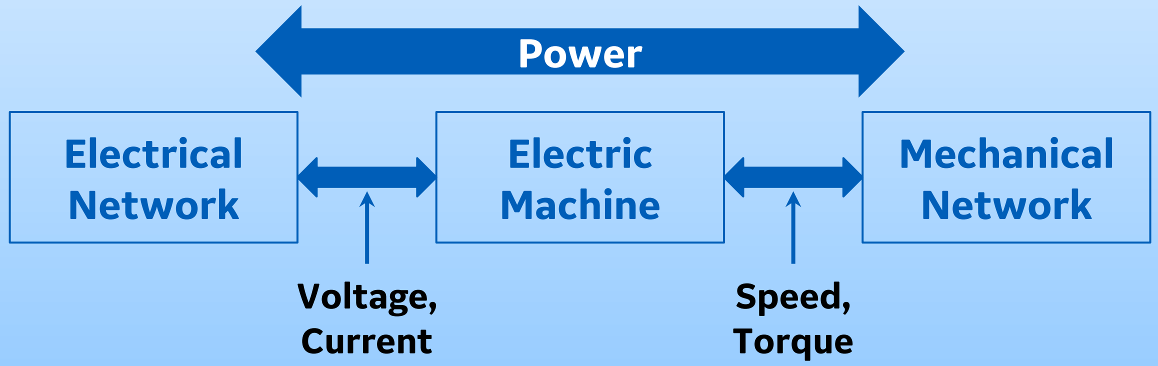
Gas tanks with convective TS cooling

- Helium gas tank integration shape and assembly within thermal shield in confined regions
- Manufacturing cost, stresses during cooldown, high initial helium pressure bearing
- Initial warm helium gas charging pressure: about 8 MPa
- Some components cannot bear this initial, high helium gas pressure and shrinkage (300 K warm part connected to a radially shrinking cold part)



Torque tube

Energy Conversion Principles



$$P \propto n\, L\, D^2\, \sigma\, \beta$$

Utilization Factors

***Magnetic*: Flux density**
- ➢ Magnetic Materials

***Thermal*: Heating from current**
- ➢ Insulation Materials
- ➢ Cooling systems

***Kinetic*: Material Strength**
- ➢ Machine architecture
- ➢ Magnetic / Structural Materials

Torque Density

$$\frac{T}{D^2 L} \propto \sigma\, \beta$$

- Volumetric torque density requires high shear stress

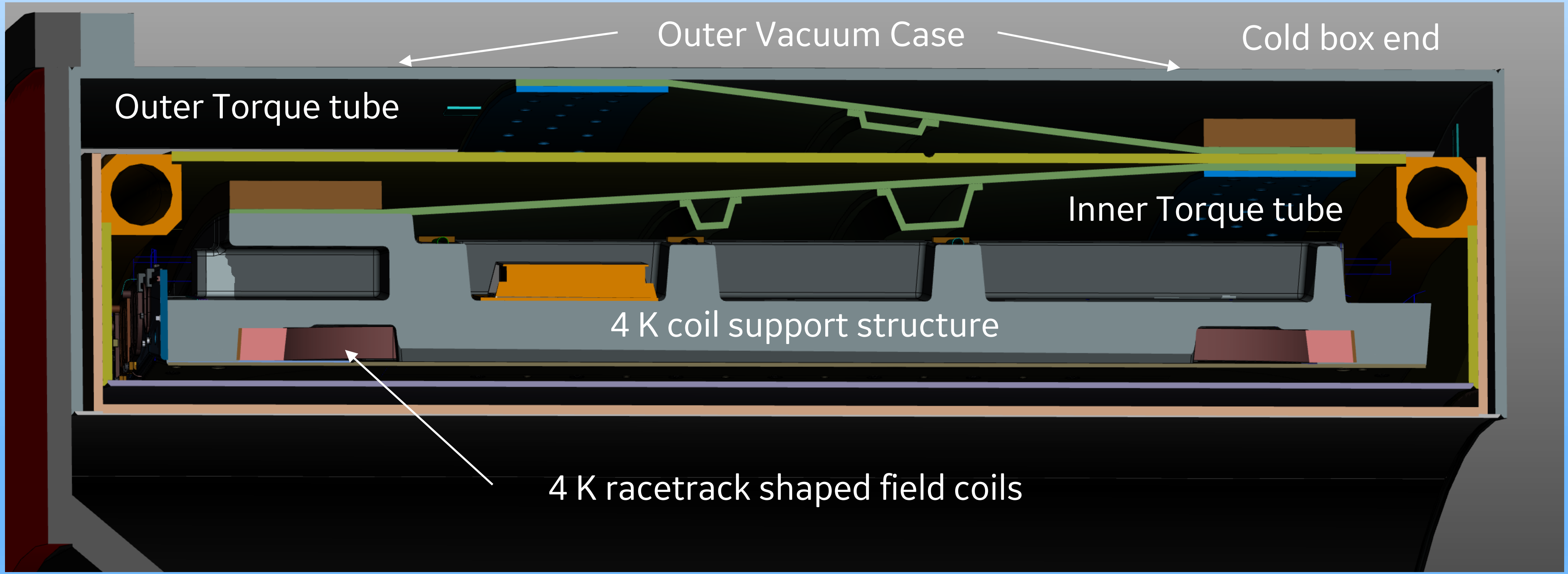
Torque Efficiency

$$\frac{T}{\sigma} \propto L D^2 \beta$$

- High efficiency driven by high magnetic loading (if magnetic loading is efficient)
- Higher efficiency pushes toward higher volume

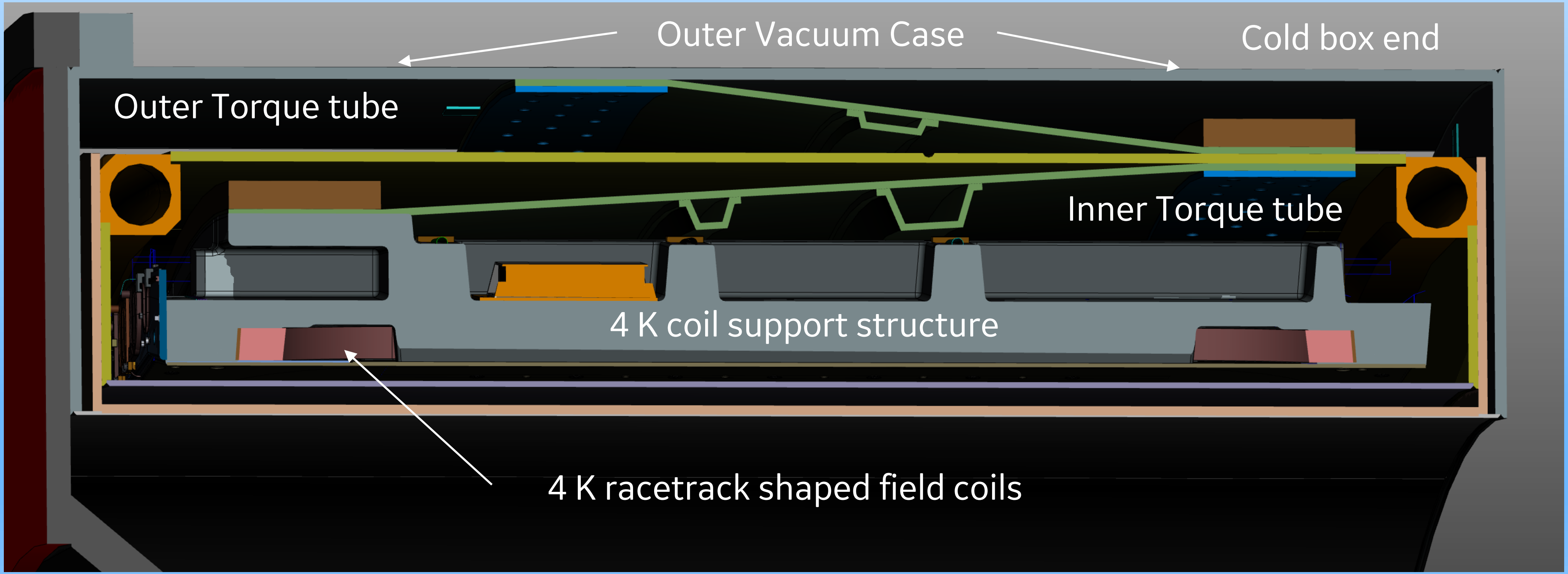
SC generator – Cryogenic Challenges (IV)

- Inner torque tube to provide uniform temperature enclosing the 4 K field coils
- Outer torque tube to provide uniform temperature partially enclosing the thermal shield (50 K)
- *Advantage*: if done well, torque tube can act as an additional thermal shield
- Sectioned instead of single composite torque tube – conduction cooled only through thermal shield



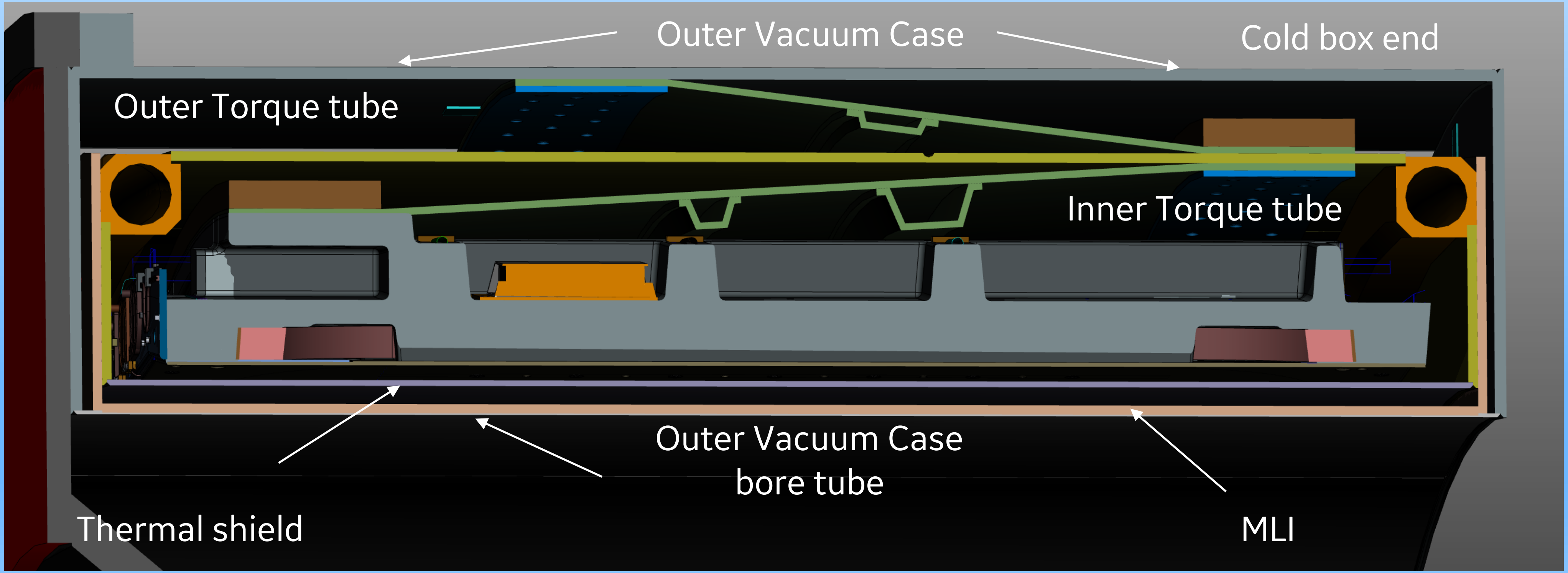
SC generator – Cryogenic Challenges (IV ctd.)

- Torque tube design and possible assembly and manufacturing capability
- Large radial shrinkage of cryogenic surface of > 20 mm causing stress concentrations on large and even small components (bellows, connecting tubes)
- Thermal shrinkage of components and load bearing elements – torque tube
- Outgassing of a large composite structure



MLI, TS, TT and coil support structure

- Moving MLI on TS due to torque rocking motion (20 mm) + shrinkage (total length/blanket: 30 m)
- Securing MLI against movement using pins (similar to space applications), cost, stresses during cooldown, assembly of blankets that need to follow the overall structural assembly plan
- TT: **lateral** conduction, wrapping mode, optically black if no reflective foil is used
- Various tapes for using those on a G10 surface have been validated (Uni Dresden)
- Assembly of 4 K MLI – bearing in mind “4 K emissivity anomaly”, deviation from Drude model



SC generator – Thermal Budget Overview

Operational-state losses	1st stage	2nd stage
Component		
Switch	0	0
Quench protection circuit loss	0	0
High-current leads	20	0.05
Instrumentation	1	0.1
Radiation losses	113	1.0
Residual gas conduction		0.1
Torque tube	60	3.3
Thermal shield eddy current loss	30	0
Coil former eddy current loss	0	0.4
Superconductor losses	0	0.2
Cold head sleeve conduction (6 sleeves)	24	0.38
Coldhead (2 stand-by)	22	1
Total losses (W)	270.4	6.53
Total cooling power (W)	270.4	6.53
1st & 2nd stage cryocooler temperature (K)	33.8	4.06
ΔT due to interface and conduction loss	6.5	0.15
Target T at top of TS and CM	40	4.2
Final T at top of TS and CM (± 1%)	40.3	4.21

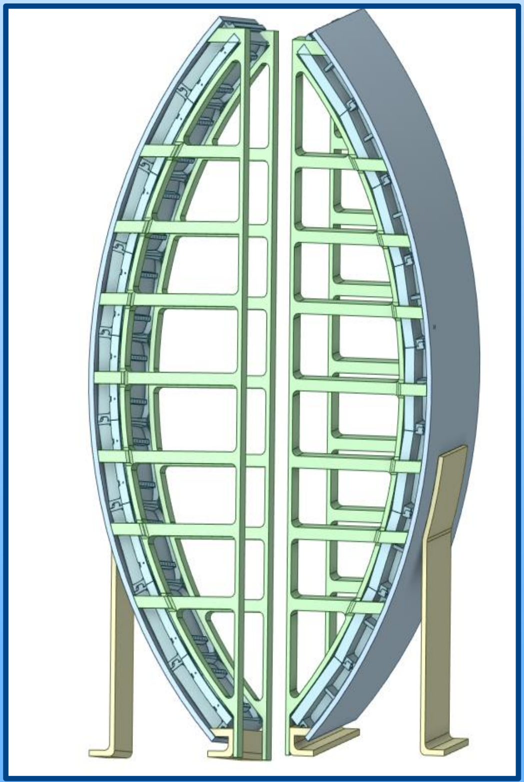
Needs to be done for all operating conditions

Loss tables generated for:

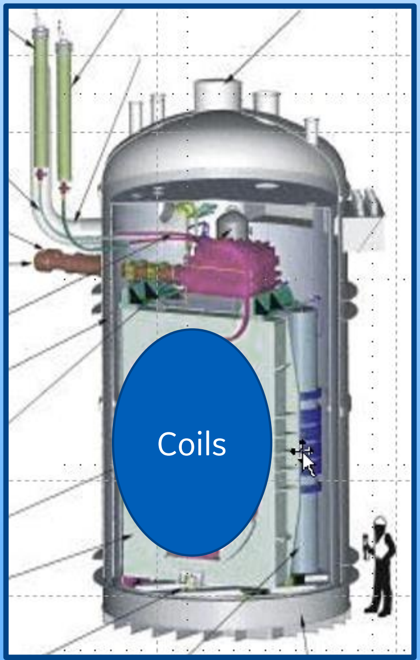
- Operational state
- Static state
- Ramp up
- Ramp down
- Ride through
- Magnet quench
- Recooling on Tower

SC generator – Cryogenic Challenges - Other

Testing superconducting coils – 16 coil test



Test bed: In-ground vacuum chamber
5 m diameter,
7.5 m deep



YES!

- You still need to run some serious magnet coil tests before you assemble all of them and you learn one of those does not work
- Some components cannot bear the high initial helium gas pressure and the shrinkage
(300 K warm part connected to a radially shrinking cold part)
- Torque tube needs to be a composite material that is knowing for heavy outgassing

Summary and Outlook

Conclusions

- ❑ Risk assessment completed
- ❑ Hit design related roadblocks for manufacture and assembly (work flow and cost)
- ❑ Getting to material property limits (cast aluminum), probably need to create new materials for this application
- ❑ Developing a superconducting prototype that is less expensive than current PMGs is not feasible
- ❑ With a SC generator, understand, that this needs a serious investment in cryogenic infrastructure

⇒ **Design pivot required**

➢ Is this the best what we can do cryogenically?

Further publications at MT 28

THANK YOU!

Internal:
- **GE Vernova** for all processes and countless discussions to ensure assembly can be run in the field (EHS etc.) the GE Vernova Research Team for their support in analysis and generating the CAD drawings, huge effort of > 50+ team members at some times
- **GE Healthcare** for all Freelium® related processes and helpfule reviews

Externals:
- **Beyond Gravity** (formerly RUAG) for their excellent support on the tricky insulation part
- **Kisters** 3D View station team for the effortless import of Siemens NX CAD models and other CAD software
- **KIT** for their generous support during materials' testing, material characterization e.g., outgassing tests etc.
- **University of Dresden** for their "tape adhesion" testing
- **Visioneering** on their vision on the detailed robotic assembly process
- **Redline** for their efforts in building a vacuum chamber
- **ANSYS** Thermal Desktop and CFD software team

- **SHI** for their dedicated GE cryocoolers and support
- **Bluefors** (formerly Cryomech) for their high-efficiency precoolers for cooldown coil test facility
- **Linde** for many in-depth discussions on cryoplants for SC generator