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This presentation was given at EFATS 2022, August 30-31, 2022.

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Superconducting flux modulation machines for hybrid and electric aircraft

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- Project FROST: Design
- Project FROST: Construction

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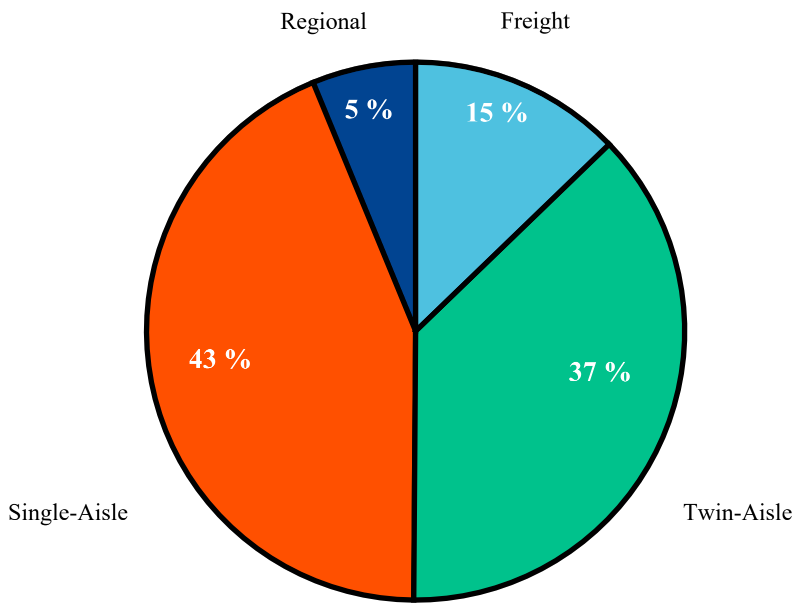
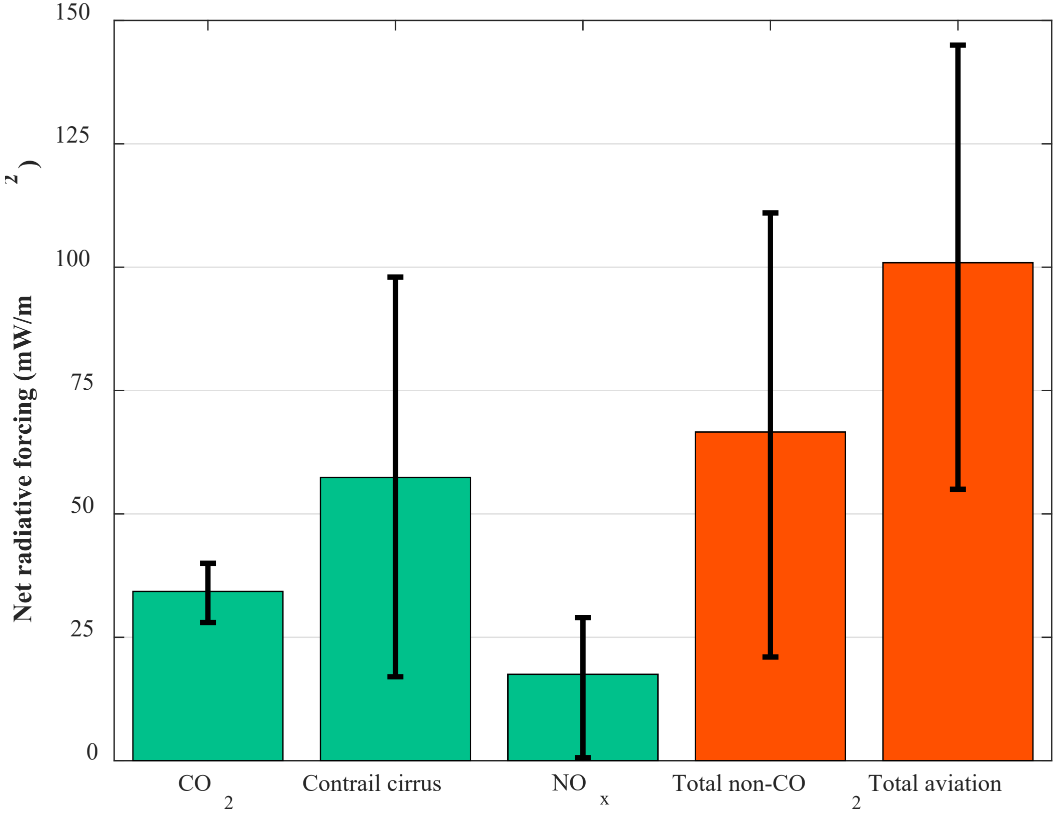
Climate impact of aviation





[1] B. Graver, D. Rutherford, and S. Zheng, "CO2 emissions from commercial aviation: 2013, 2018, and 2019," The international council on clean transportation, Oct. 2020
[2] Lee, D. S., Fahey, D. W., Skowron, A., Allen, M. R., Burkhardt, U., Chen, Q., ... & Wilcox, L. J. (2021). The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. Atmospheric Environment, 244, 117834.

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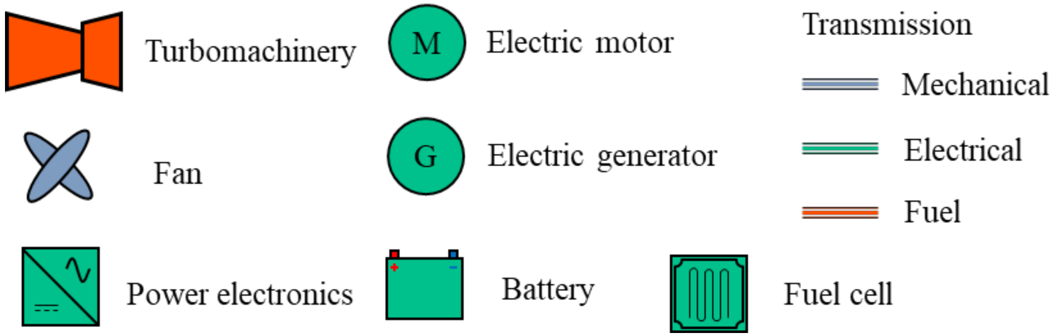
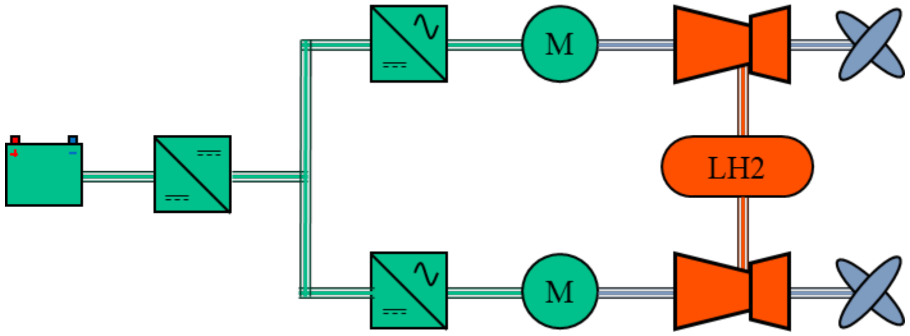
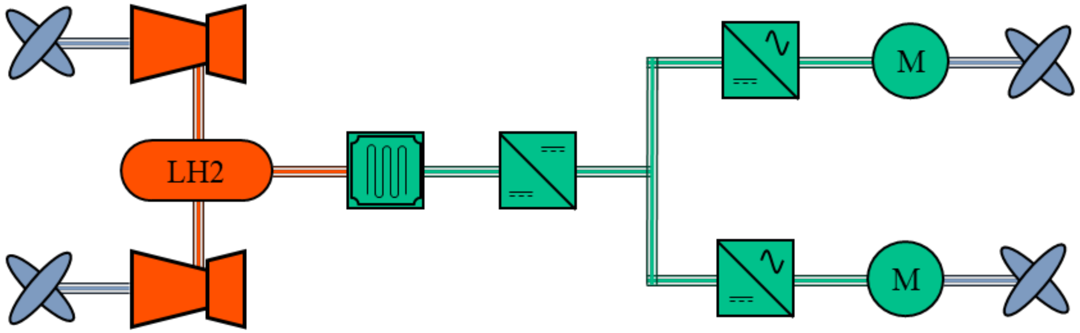
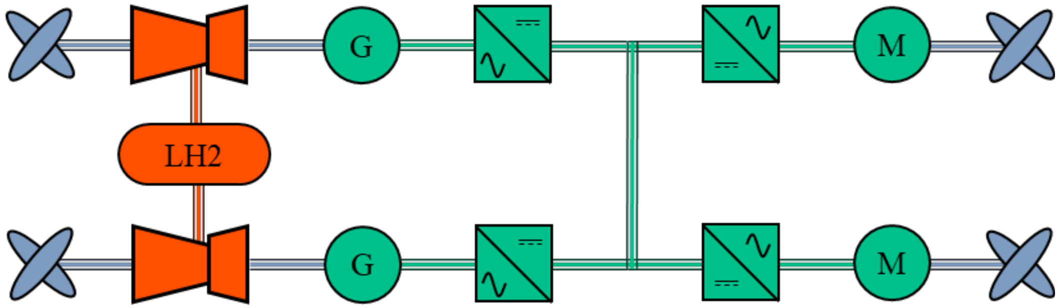
Electric architectures









Turboelectric

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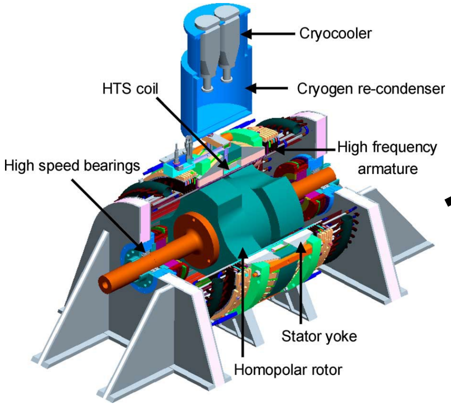
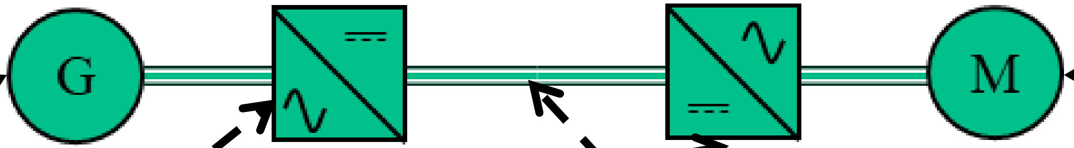
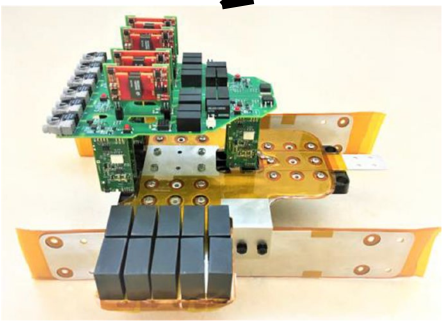
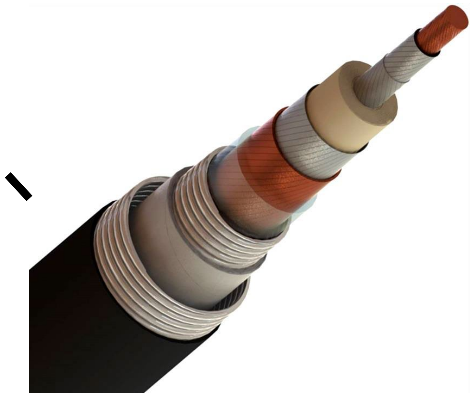
HTS & cryogenic technologies

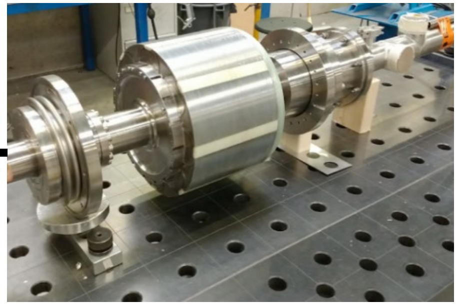
- High temperature superconductivity (HTS) and cryogenic technologies can increase the specific power and efficiency of the powertrain
- Liquid hydrogen (LH2) (~20K) as auxiliary or primary fuel can overcome the main obstacle of HTS : the cooling











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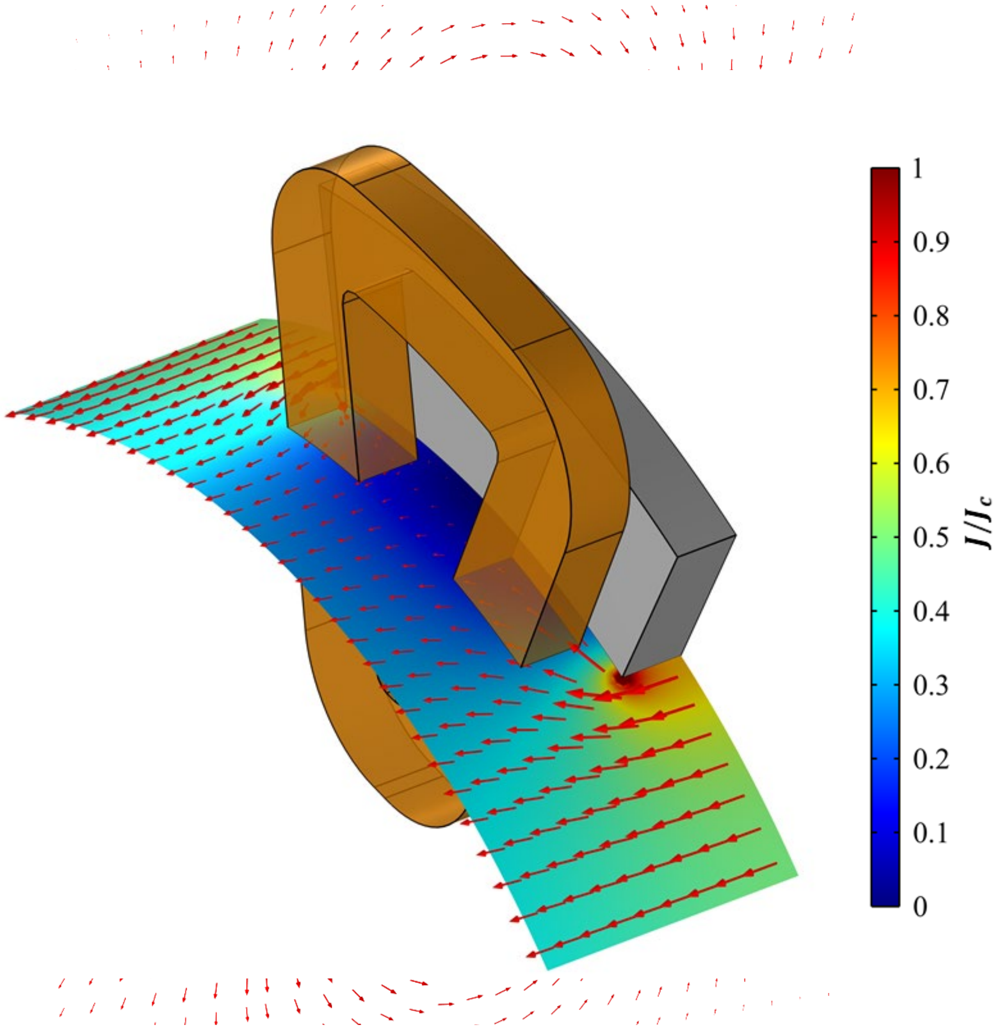
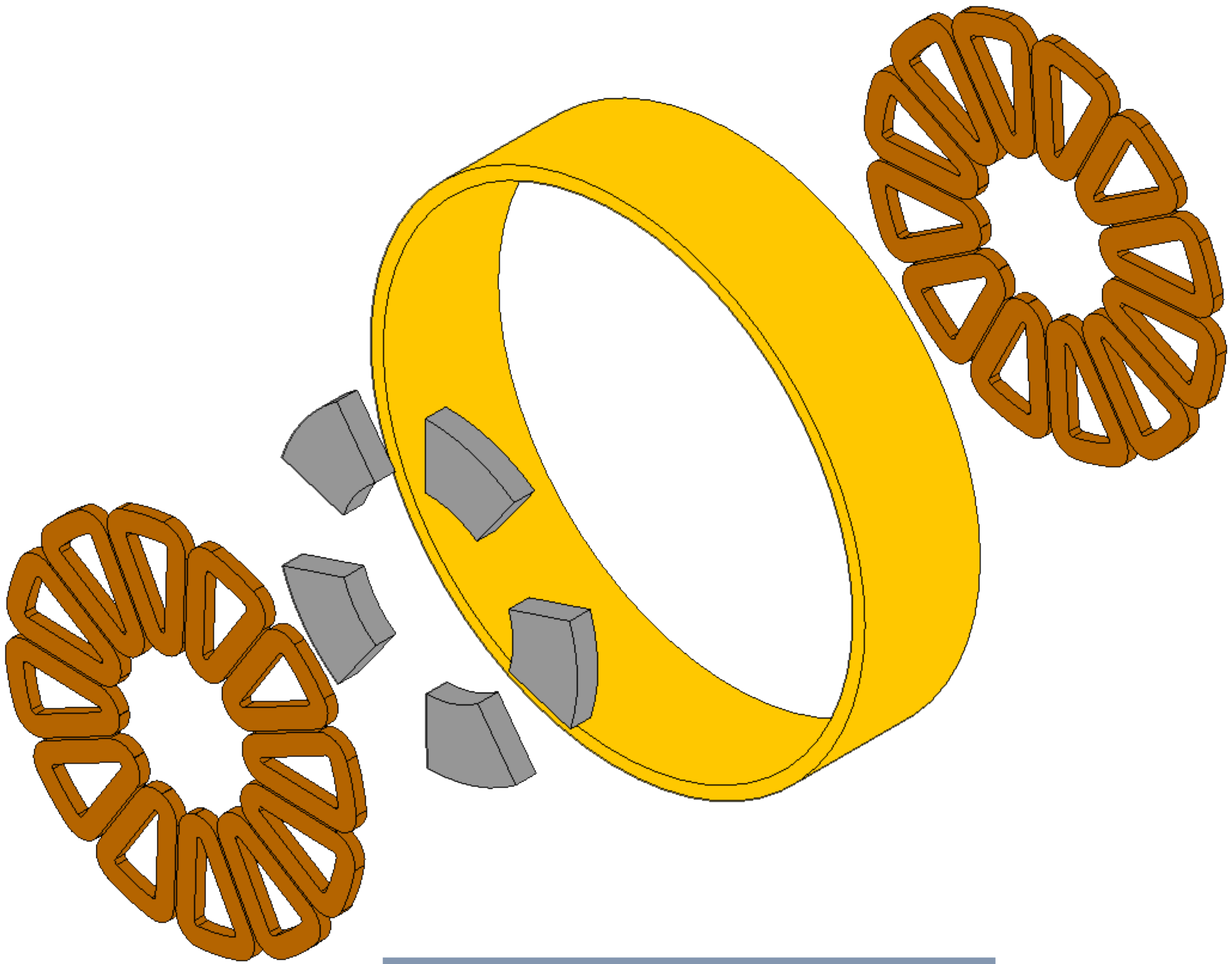
Flux modulation machine





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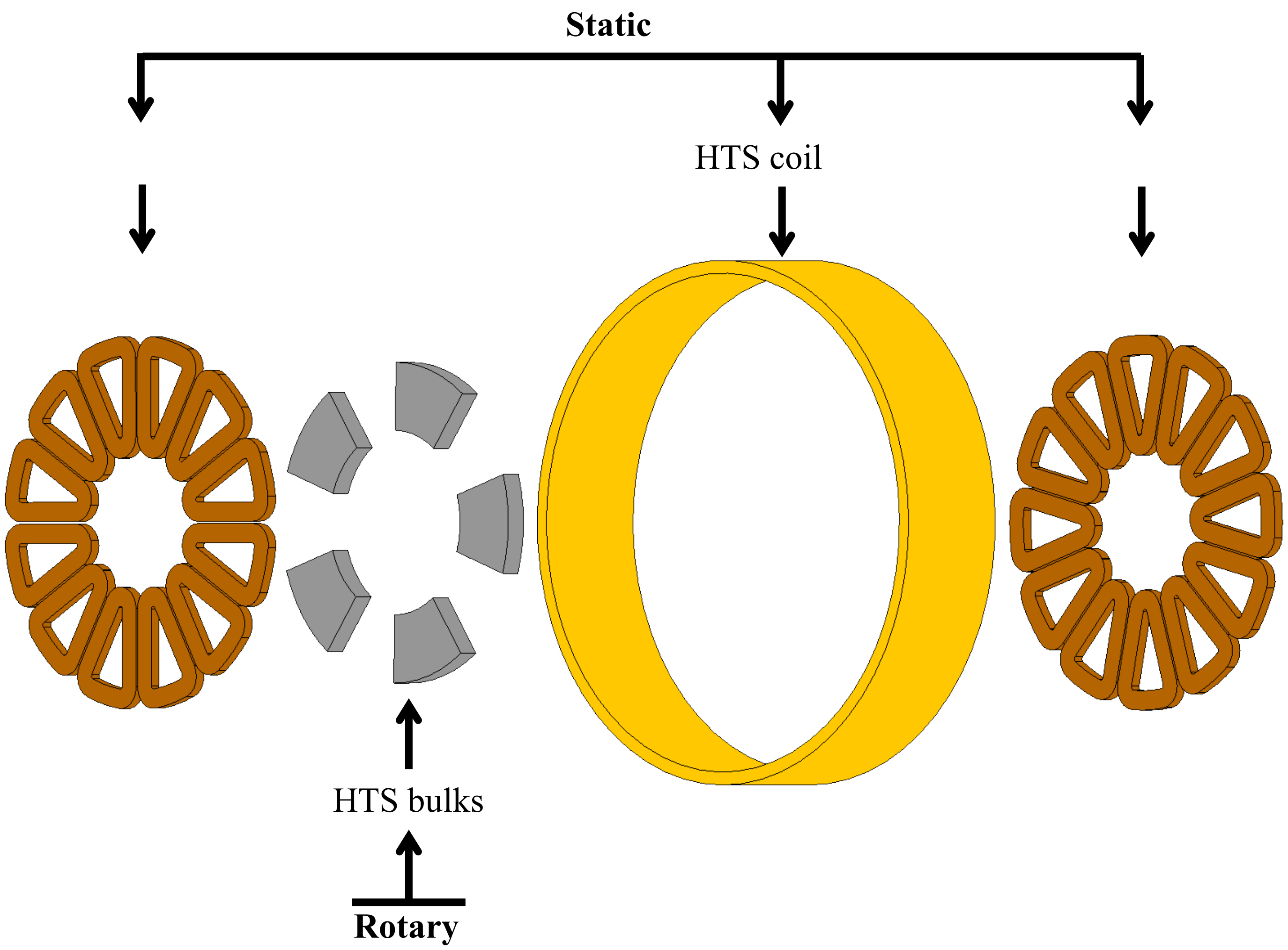
Flux modulation machine

- 3-phases AC synchronous
- Axial flux
- Air cored
- Brushless
- Inductor flux density controllable from the HTS coil



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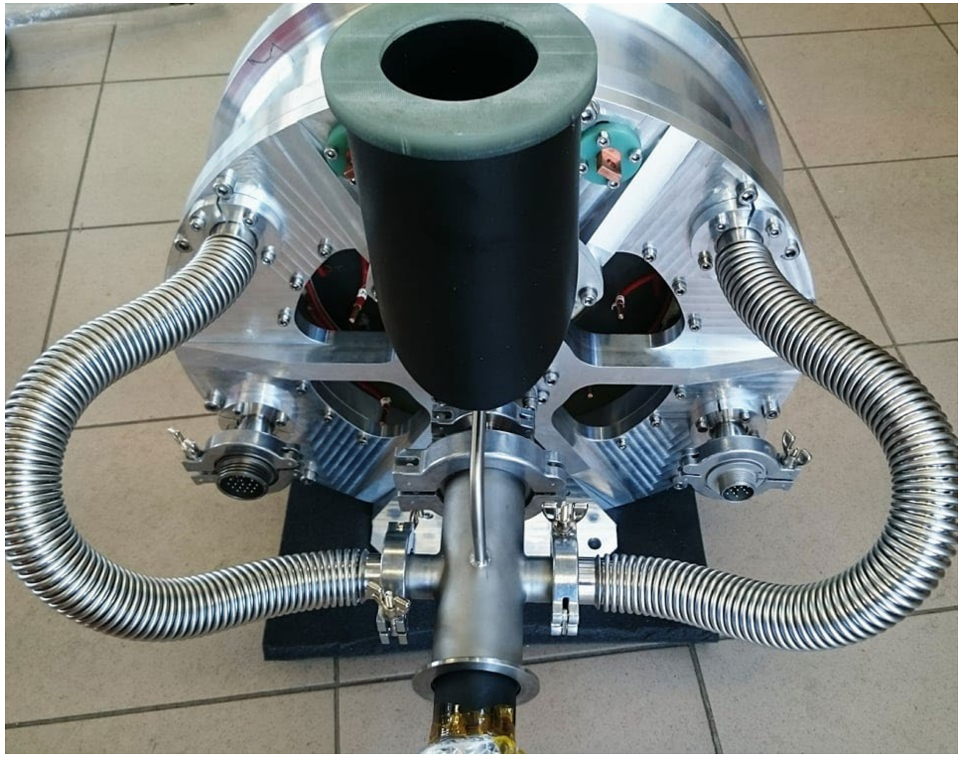
Project RESUM

REalisation of a SUperconducting Motor (RESUM):

- Partially superconducting 50 kW proof of concept built in summer 2019
- Rated values:
  - ❖Ø = 470 mm
  - ❖Length = 200 mm
  - ❖M = 52 kg
  - ❖Ω = 5000 rpm



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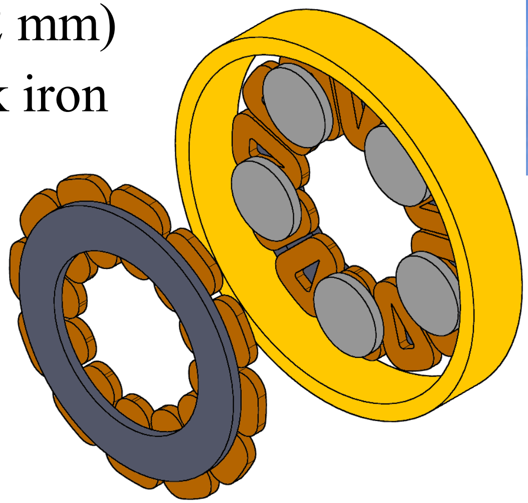
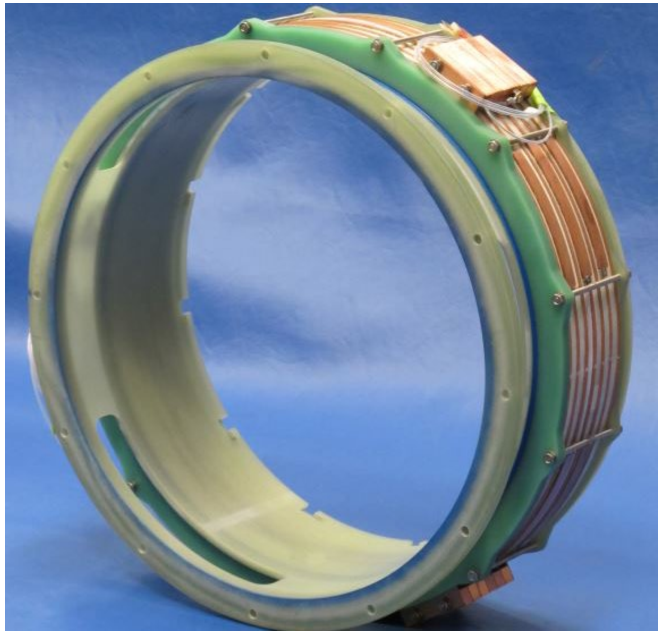
Project RESUM

- Inductor:
  - ❖1G HTS coil (BiSrCaCuO)
  - ❖HTS disk shaped bulks (YBaCuO)
  - ❖Working temperature : 30 K
- Armature:
  - ❖Copper Litz wire 20 AWG (Ø = 0.812 mm)
  - ❖Small back iron





Picture of the rotor

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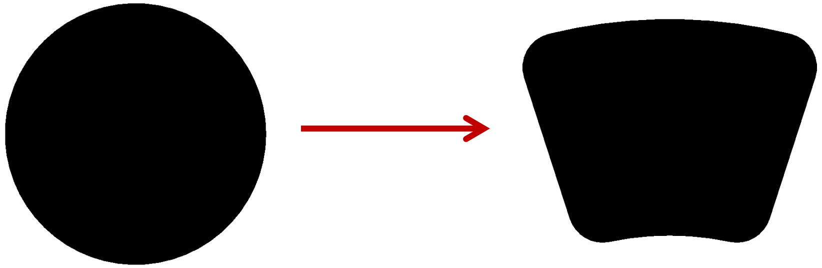
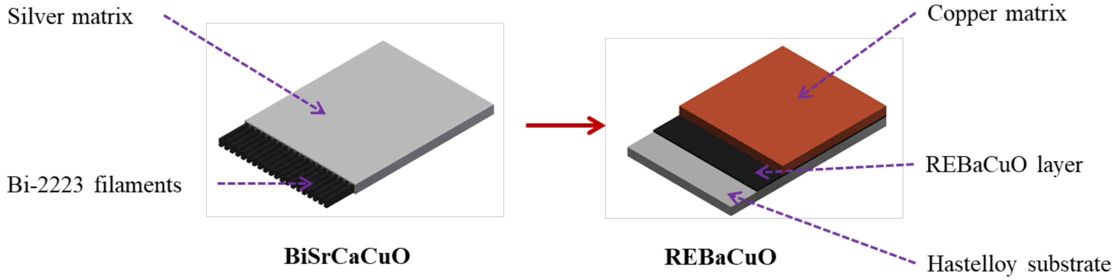
FROST: Principle

- Flux-barrier ROtating Superconducting Topology (FROST):
  - ❖Started in 2020
  - ❖Partially superconducting demonstrator

- Project philosophy:
  - ❖Change bulks shape
  - ❖Change HTS coil material (Critical current x3)
  - ❖Add liquid cooling to the armature (goal : 30 A/mm²)

→ Unviable design as it stands





Parameter	RESUM	FROST (pre-sizing)
Ω	5000 tr/min	
P	50 kW	373 kW
M	52 kg	42 kg
PtM	1 kW/kg	8,9 kW/kg
η	94 %	92,8 %
Ø	470 mm	470 mm

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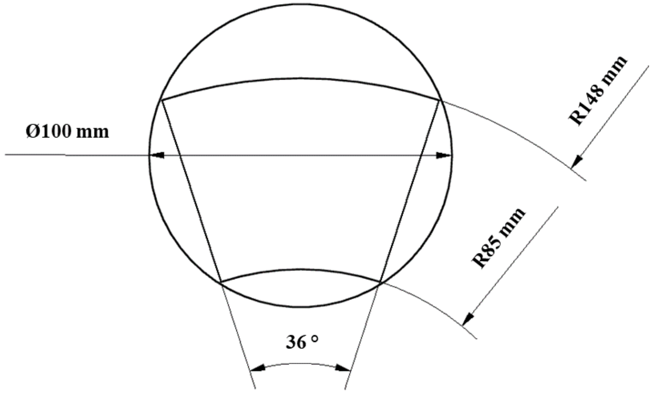
HTS bulks design

- Ring segment shaped bulks are machined from disks
  - ❖Maximum available size commercially in single domain is **Ø 100 mm**
  - ❖Bulk size has been reduced by 33 % because of this limit

- In 2022 : **Ø 155 mm** achieved by CAN [8]



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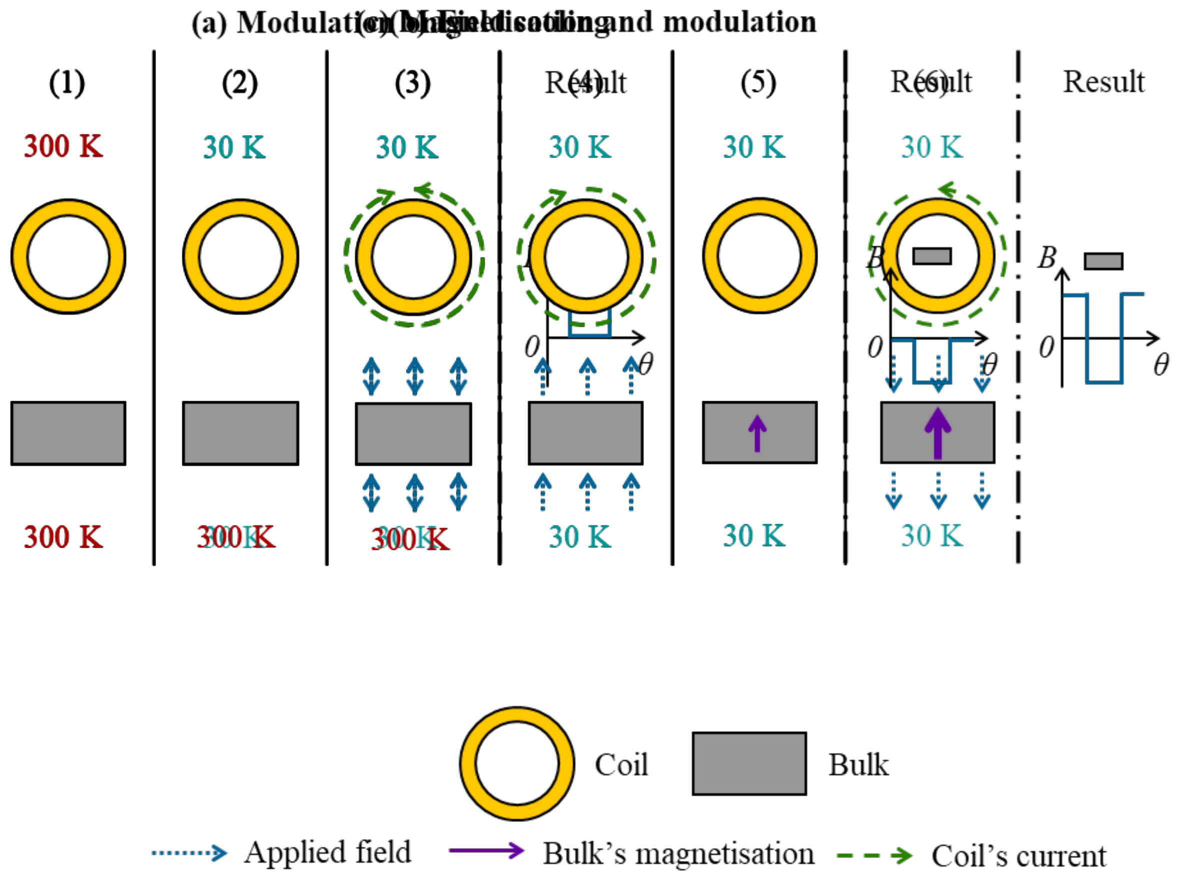
Working modes



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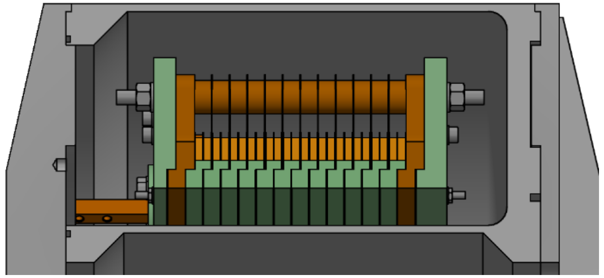
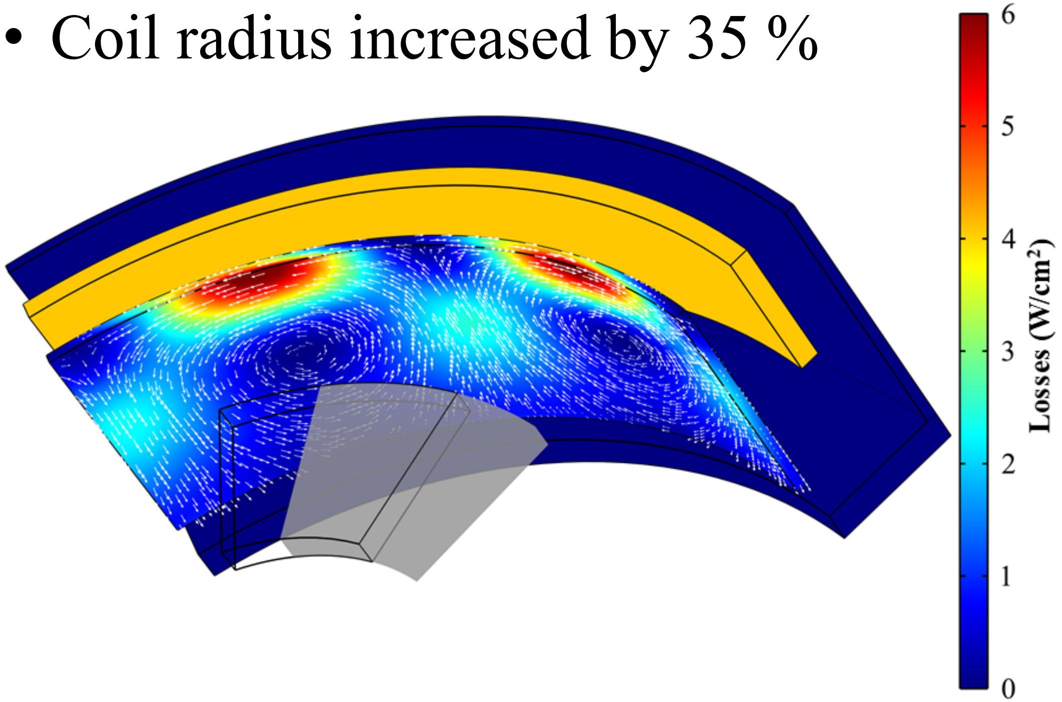
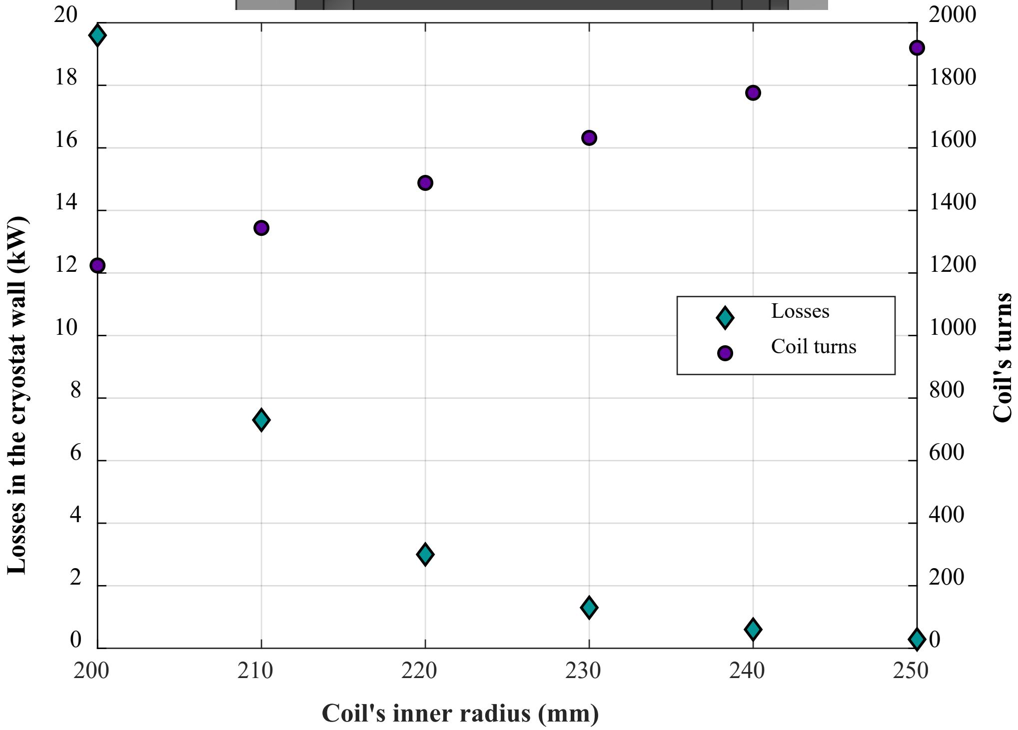
Losses in the coil cryostat

- The coil cryostat is manufactured in aluminum
  - ❖ AC losses are generated in the cryostat wall
  - ❖ Distance between rotor and cryostat must be increased to mitigate the losses
- Coil radius increased by 35 %







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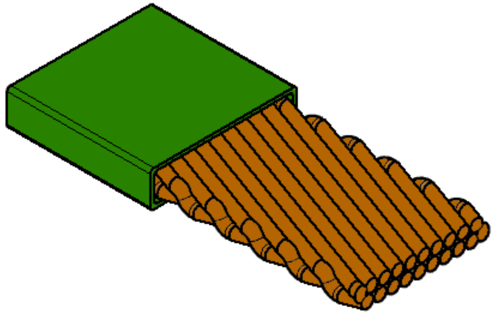
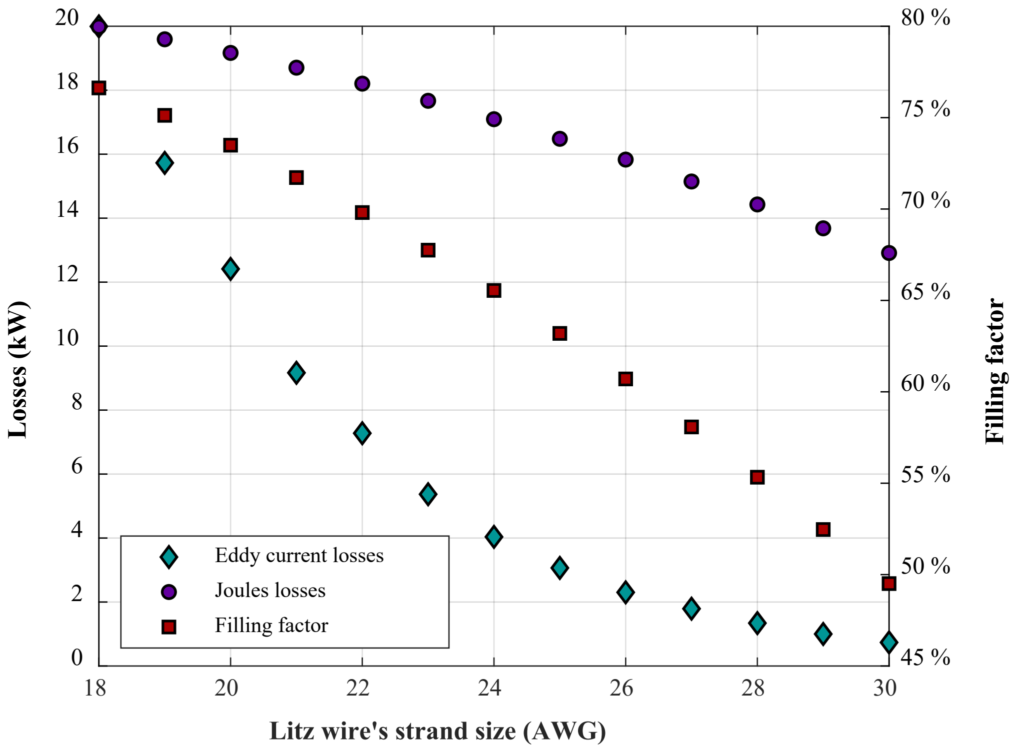
Eddy current losses in Litz wire

- Due to the absence of iron teeth :
  - The armature is subjected to the inductor field
  - Eddy-current losses are generated in the amarture wires
- Litz wire with small strand size must be use
  - Reducing strand size mitigates the losses
  - Small strand Litz wire have a worse filling factor
  - 20 AWG → 28 AWG





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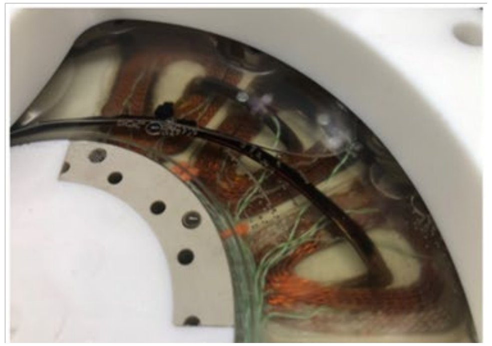
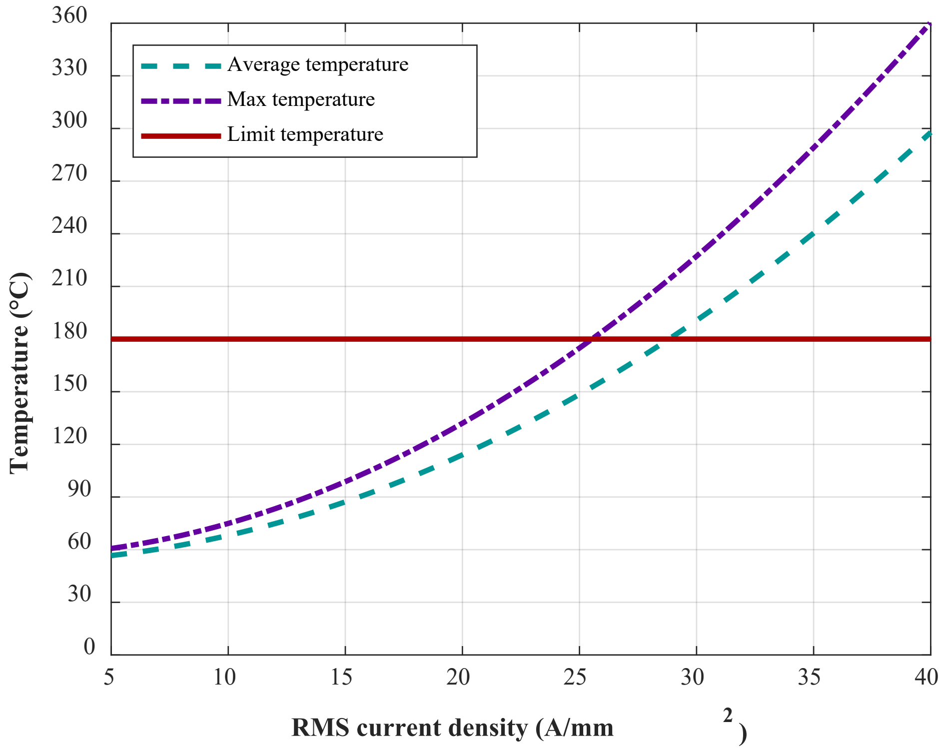
Amarature's liquid cooling

- The limited filling factor of the Litz wire implies a low thermal conductivity (6,8 W/mK)
- The expected current density in the stator is 25 A/mm^2 instead of 30 A/mm^2





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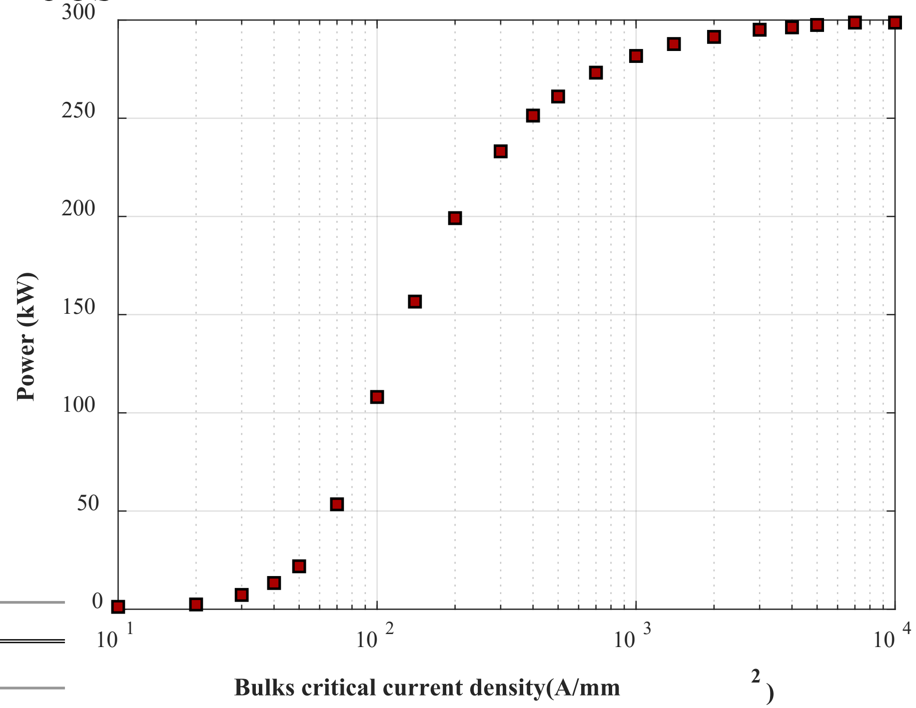
Expected performances

Several limitations have reduced the expected performances

- Technical limitations:
  - ❖Single domain REBaCuO bulk size
  - ❖Losses in cryostat wall
  - ❖Litz wire small filling factor
  - ❖Difficulty to cool the stator
- Project issues:
  - ❖Reduced budget for the coil purchase
  - ❖Litz wire availability



Parameter	RESUM	FROST
Ω	5000 tr/min	
P	50 kW	261 kW
M	52 kg	148 kg
PtM	1 kW/kg	1.8 kW/kg
η	94 %	95.3 %
Ø	470 mm	630 mm

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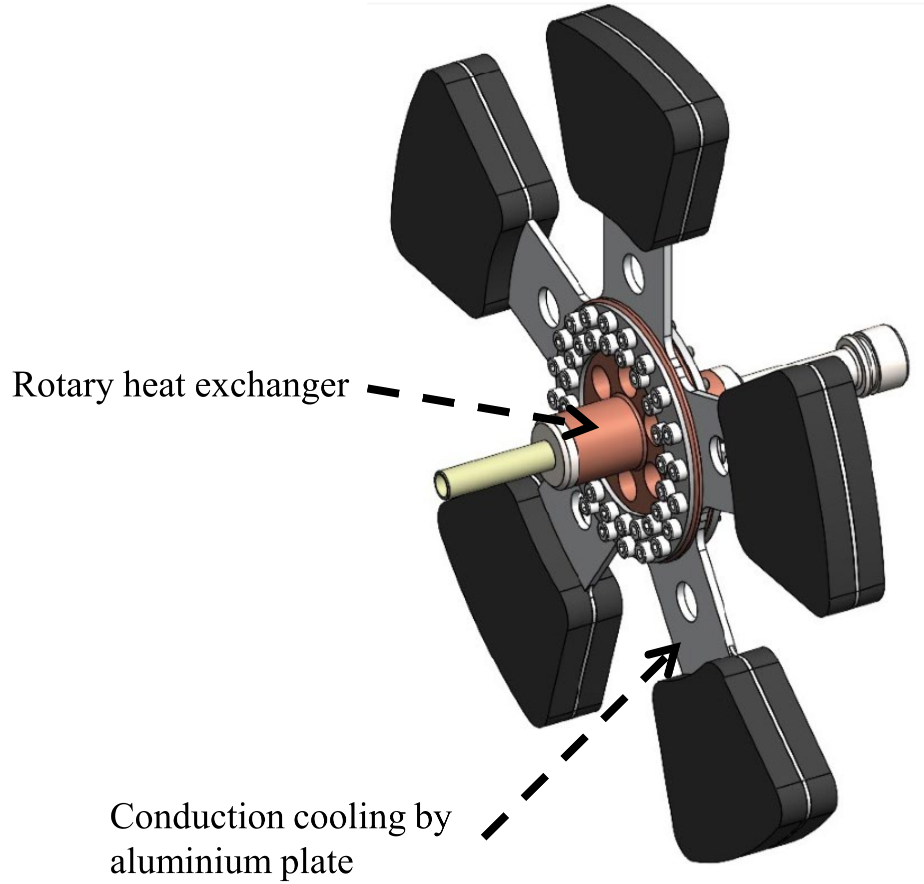
Rotor and bulks

- New cryogenic cooling for the rotor:
  - ❖ Bulks are cooled by an aluminum plate in between 2 bulks
  - ❖ The number of bulks has been doubled (5 pole pairs → 10 bulks total)



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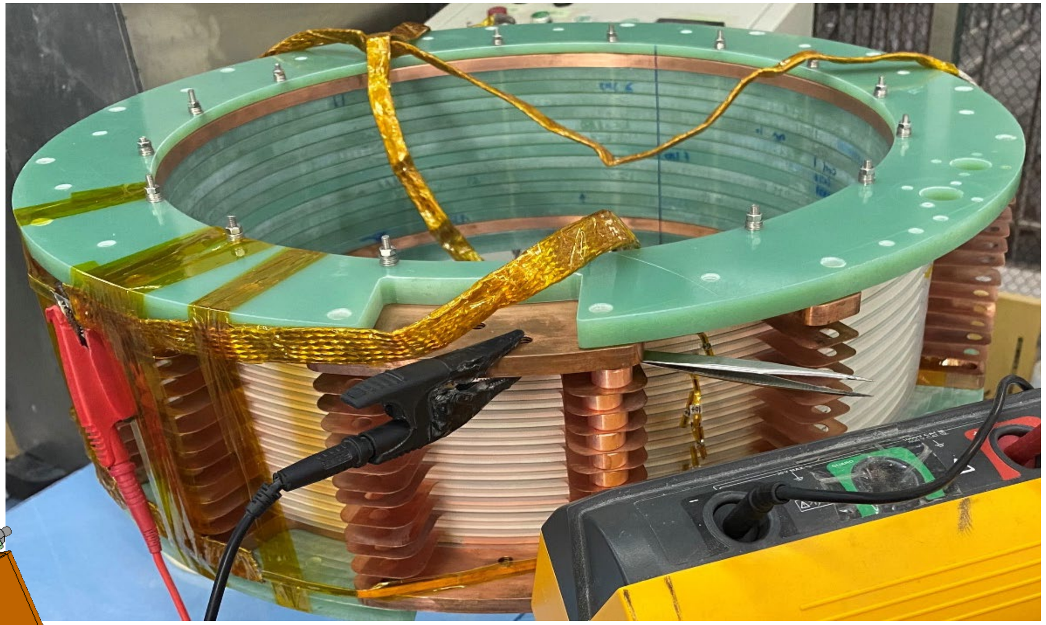
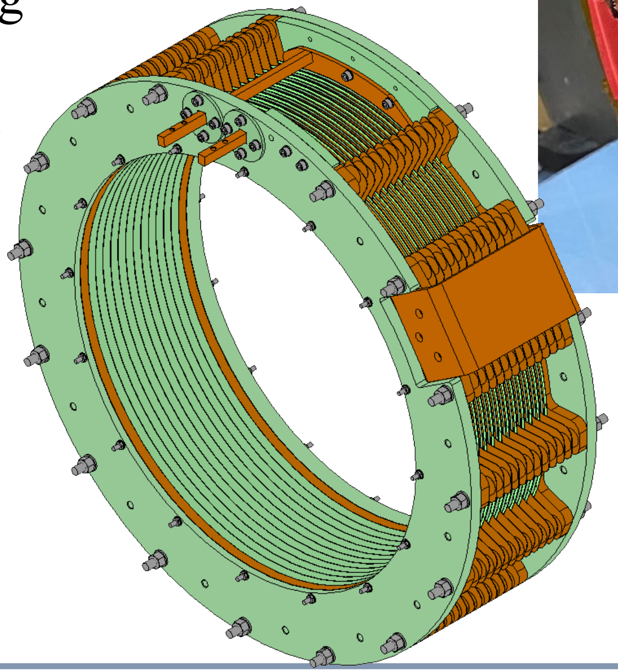
HTS coil

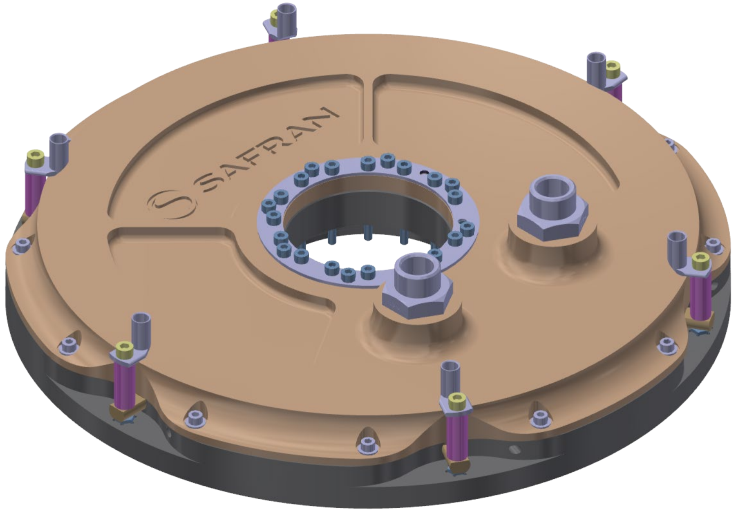
- Coil ordered from SHSTEC
  - ❖3420 m of HTS tapes
  - ❖38.4 kg
    - HTS tapes: 13.5 kg
    - Copper: 16.7 kg
    - G10: 6.5 kg
    - Screws & bolts: 1.7 kg





Armature

- Winding completed
  - ❖ 10 kg per amarature
    - Litz wire: 2.7 kg
    - G11: 6.3 kg
    - Misc: 1 kg



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Conclusion

- Full assembly of the demonstrator planned for 2023
- Rated power expected 261 kW
- Several options to further increase power:
  - ❖Bulk size available commercially is increasing
  - ❖High thermal conductivity Litz wire
  - ❖Improvement in 2G HTS wire

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Comparison of working modes

Comparison of the 3 modes:

- Mode (a): applied field of 1 T
- Mode (b): applied field of 1 T
- Mode (c): applied field of 0,5 T

Three modes are equivalent except for the average value