Superconducting flux modulation machines for hybrid and electric aircraft

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Outline

- Introduction
- Flux modulation machine
- Prior works: Project RESUM
- Project FROST: Principle
- Project FROST: Design
- Project FROST: Construction

- Agence Nationale de la Recherche (ANR)
- Agence de l’Innovation de Défense (AID)
- Direction Générale de l’Armement (DGA)
Climate impact of aviation

Electric architectures

Turbomachinery → Electric motor

Fan

Electric generator

Power electronics → Battery

Transmission
- Mechanical
- Electrical
- Fuel

Fuel cell

LH2 → M → LH2

Turboelectric
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
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:
  - $\varnothing = 470$ mm
  - Length = 200 mm
  - M = 52 kg
  - $\Omega = 5000$ rpm
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
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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
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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]
Working modes

(a) Modulation and modulation

<table>
<thead>
<tr>
<th>(1) 300 K</th>
<th>(2) 30 K</th>
<th>(3) 30 K</th>
<th>Result 30 K</th>
<th>Result 30 K</th>
<th>Result 30 K</th>
<th>Result 30 K</th>
</tr>
</thead>
</table>

Coil      Bulk

Applied field  Bulk’s magnetisation  →  Coil’s current
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%
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 armature wires

• Litz wire with small strand size must be used
  - Reducing strand size mitigates the losses
  - Small strand Litz wire have a worse filling factor
  - 20 AWG $\rightarrow$ 28 AWG
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/mm² instead of 30 A/mm².
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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>RESUM</th>
<th>FROST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ω</td>
<td>5000 tr/min</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>50 kW</td>
<td>261 kW</td>
</tr>
<tr>
<td>M</td>
<td>52 kg</td>
<td>148 kg</td>
</tr>
<tr>
<td>$PtM$</td>
<td>1 kW/kg</td>
<td>1.8 kW/kg</td>
</tr>
<tr>
<td>η</td>
<td>94 %</td>
<td>95.3 %</td>
</tr>
<tr>
<td>Ø</td>
<td>470 mm</td>
<td>630 mm</td>
</tr>
</tbody>
</table>
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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)
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 armature
    - Litz wire: 2.7 kg
    - G11: 6.3 kg
    - Misc: 1 kg
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
Thank you for your attention

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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.