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EFATS ELECTRIC AIRCRAFT PROPULSION

30-31 August 22, Glasgow

ASCEND

Design of partial superconducting motor:

Last brick of a superconducting and cryogenic powertrain

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Summary

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1. **ASCEND**

2. **Potential gain using superconductors**
   2.1. Electrical motor general equations
   2.2. Superconductivity on the stator side
   2.3. Superconductivity on the rotor side

3. **Design of a partial superconducting motor for aircraft applications**
   3.1. Models and topologies
   3.2. Design of a 500 kW motor
   3.3. Extrapolation to MW-class motor application

1- **ASCEND:** Advanced Superconducting and Cryogenic Experimental powertraiN Demonstrator

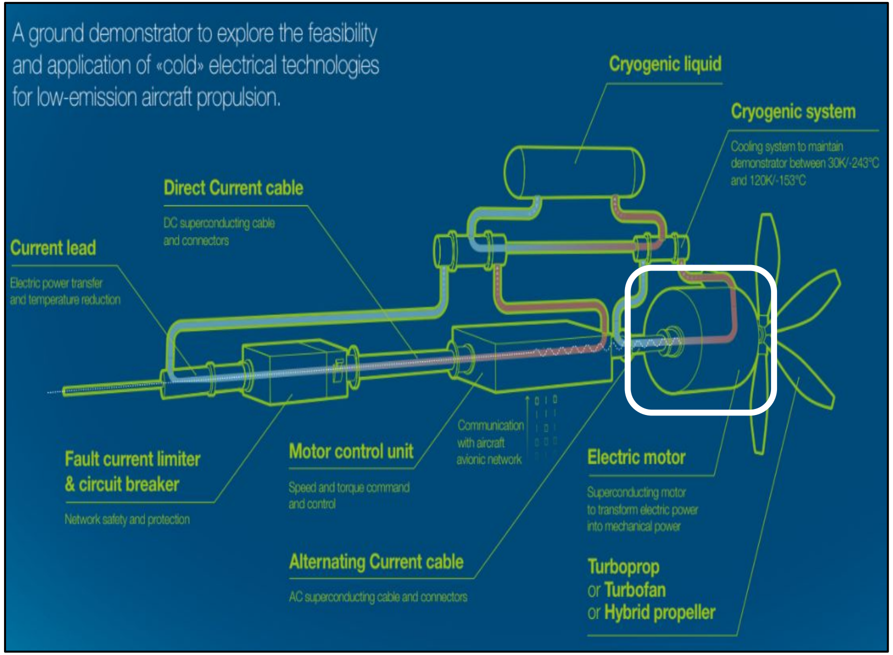

Fig 1. All components of the cryogenic powertrain

A 3 years project to manufacture and test a ground demonstrator composed by:

- A cryogenic electrical protection
- An AC and a DC distribution with SC cables
- A motor control unit cooled at cryogenic temp.
- A SC motor
- A cryogenic cooling system with the cryocooler technology for the project **BUT** could be LH2 storage in future aircraft (large cooling power)

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1- **ASCEND:** Advanced Superconducting and Cryogenic Experimental powertraiN Demonstrator

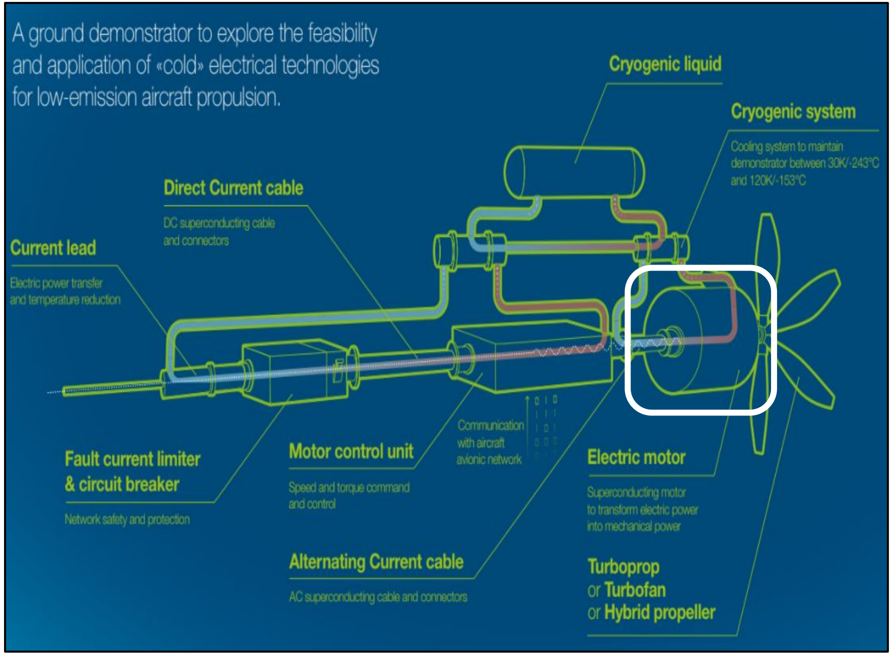

Fig 1. All components of the cryogenic powertrain

The design that will be presented here consider:

- A mechanical power of **500 kW** at **5000 rpm**
- Limit the supply voltage to a low value → V_{DCbus}= **300 V**
- Limit the power factor of the machine to a minimal value of **0,85** → Limit the switching current on the line below **1800 A**.
- Coolant at a temperature of around **25 K** and conductors below **35 K**

2- Electrical motor general equations

1. **Torque ~ Vol_rotor * Ks * Bg**

- **Vol_rotor**: volume of the rotor [m^3]
- **B_g**: Magnetic field density in air-gap [T]
  - B_g = f(PM,$1/g^2$)
- **K_s**: Linear current density [A/m]
  - Ks = Js * hss
- **Js**: Surface current density [A/m^2]
  - Copper: Js ~ 10 A/mm^2 (oil/water cooling)
  - SC: Js ~ 100 A/mm^2 (cryogenic cooling system)

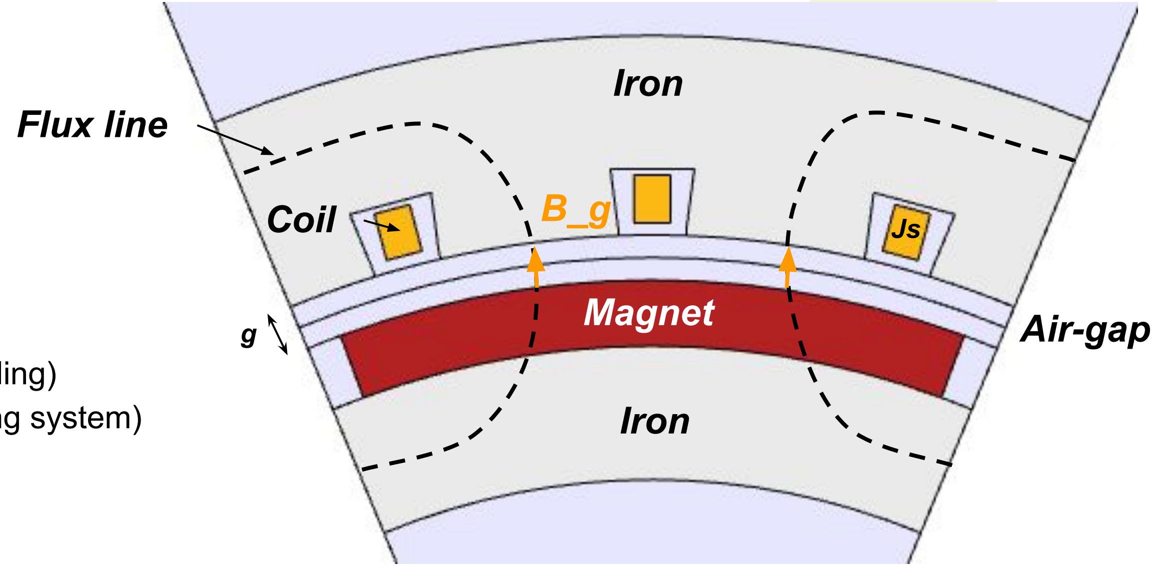

Fig. 2. Electric motor scheme

2. **Power = Torque * Rotating speed**

2- Superconductivity on the stator side

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K_s_rms: Linear current density of the stator

T = Vol_rot . B_g_max . K_s_rms / √(2) ⟶ **hs = T / (2π . R_g^3 . Asp_rat . B_g_max . J_s)**

Increase K_s_rms ⟵

⟶ *Increase Vol_rot*

Lower radius could demagnetize the PM

- ↗ Ks = ↗ Armature reaction
  - Risk of PM demagnetization
  - Increase the switching of the PE

- Impact on the AC losses ?
  - Several tapes in // to drive the nominal current

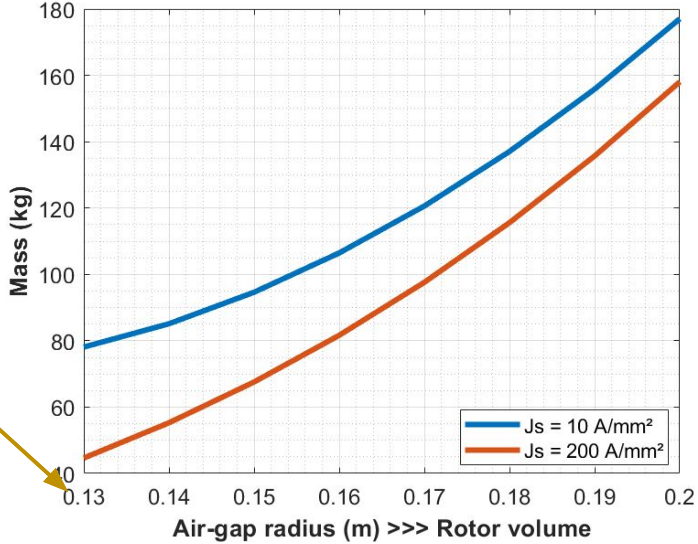

Fig. 3. Active mass versus the rotor volume

Fixed value:
T = 1000 N.m
B_g_max = 0.9 T
Asp_rat = 0.3

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2- Superconductivity on the stator side

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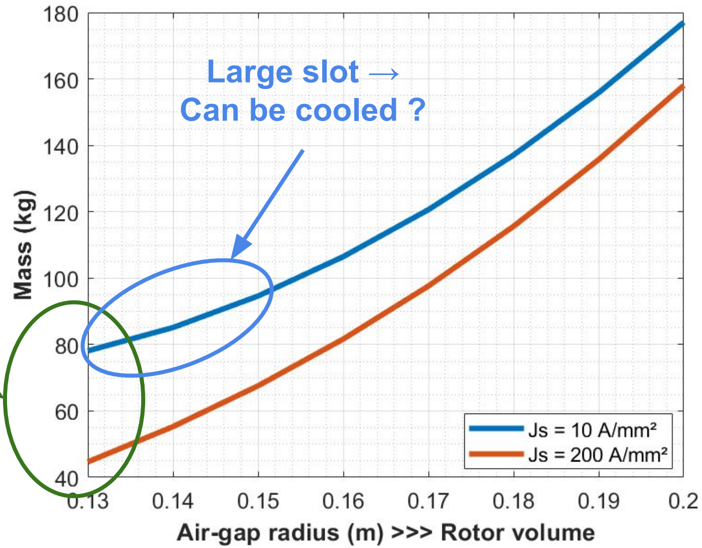
Increase K_s_rms ⟵

⟶ *Increase Vol_rot*

Mass can be divided by 2 with a SC winding on the stator

- Could be higher depending on the heat extraction system of the conventional system.
- Considering the passive components of a SC motor, what about this gain ?



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Thick slot:

- Back-iron heavier
- Thicker teeth
- Cooling of the conductors

Mass_BI ∝ (Ro² - Ri²)

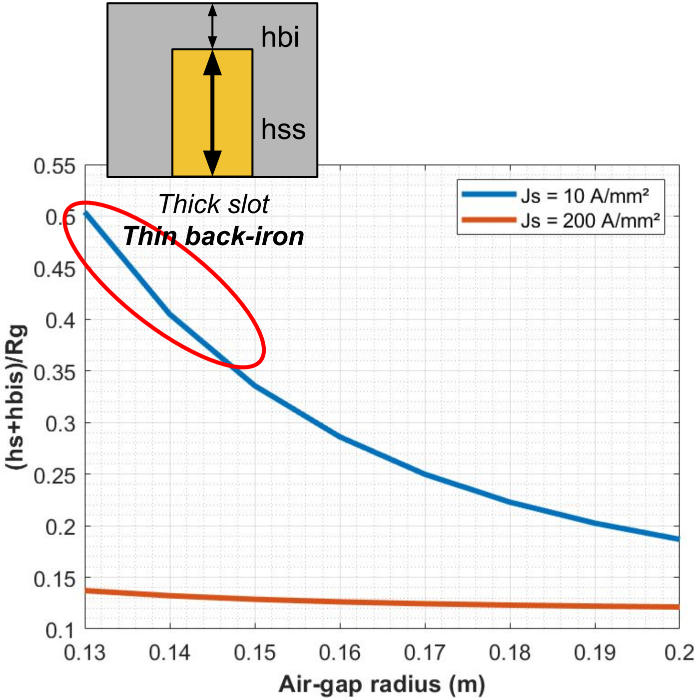

Fig. 4. Slot thickness versus the air-gap radius

Fixed value:

T = 1000 N.m

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2- Superconductivity on the stator side

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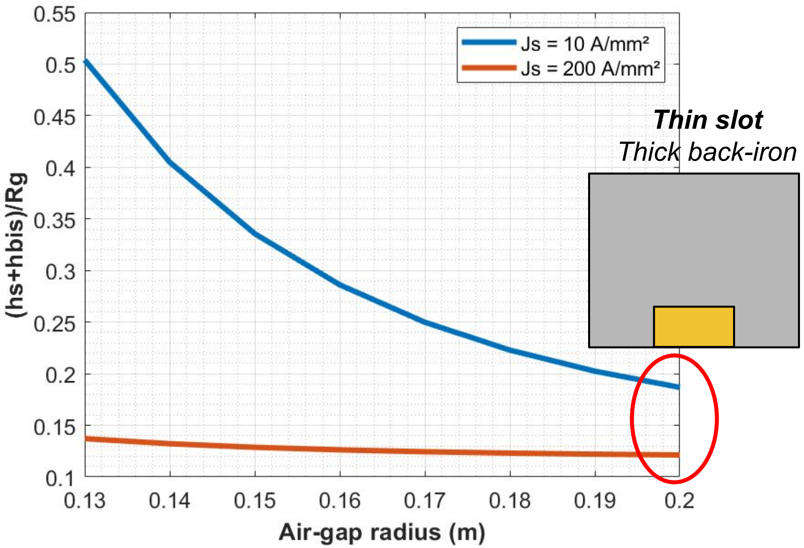

Fig. 4. Slot thickness versus the air-gap radius

Thick back-iron:

- Back-iron heavier

h_BI ∝ Arc_pole × (Bg/Bsat)

Fixed value:

T = 1000 N.m
B_g_max = 0.9 T
Asp_rat = 0.3

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2- **Superconductivity on the stator side**

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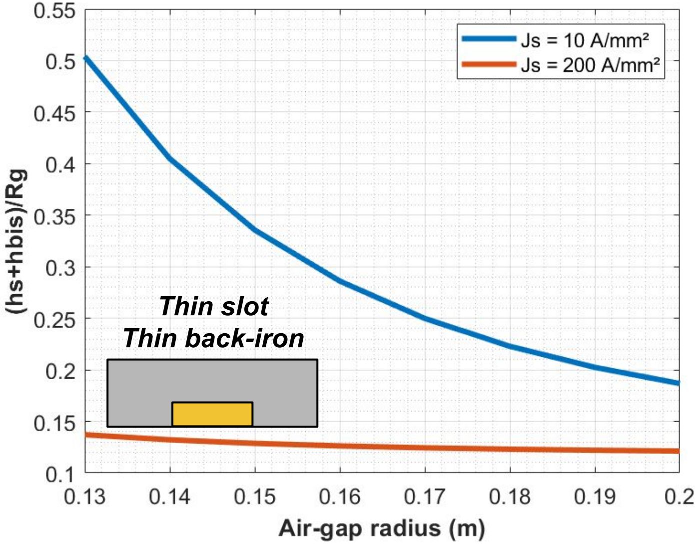

Fig. 4. Slot thickness versus the air-gap radius

Potential gain on the iron mass with a SC "cryo-copy" topology !

Fixed value:
T = 1000 N.m
B_g_max = 0.9 T
Asp_rat = 0.3

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2- Superconductivity on the rotor side

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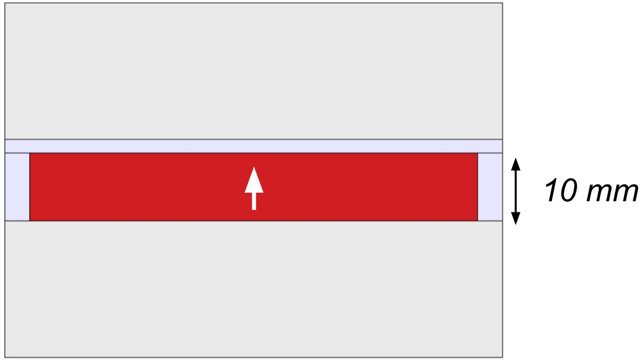
B_g_max: Air-gap flux density

T = Vol_rot . B_g_max . K_s_rms / √(2)

Magnetization with PM:



- High torque/power density
- No demagnetization possible

Fixed value:

B_g_max = 1.1 T

Look for the same flux

2- Superconductivity on the rotor side

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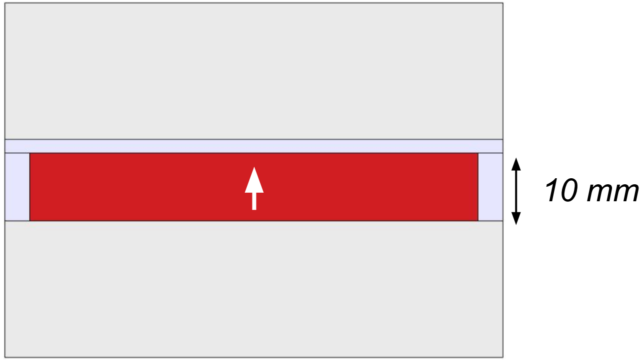
Look for the same flux

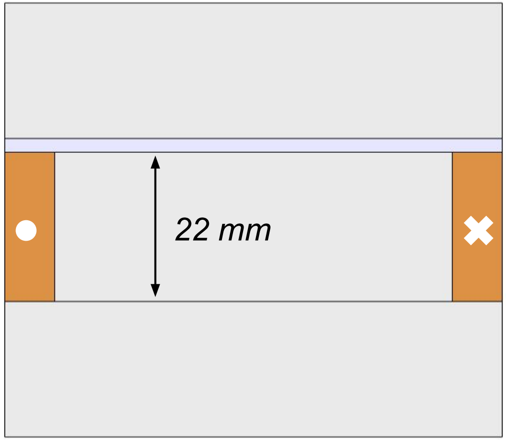
Magnetization with PM:



- High torque/power density
- No demagnetization possible

Magnetization with copper coils:

Js = 10 A/mm²



- Weight x2
- Higher losses to extract
- Armature reaction
- Stop the supply

2- Superconductivity on the rotor side

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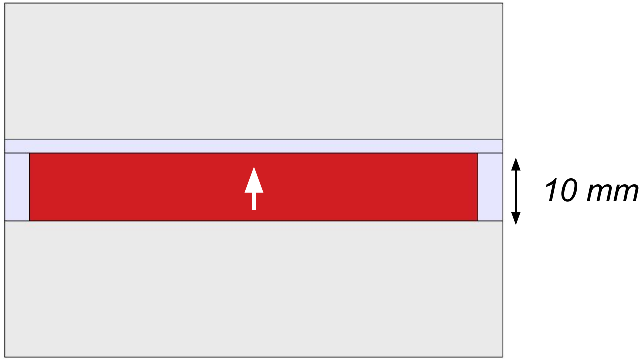
Magnetization with PM:



- High torque/power density
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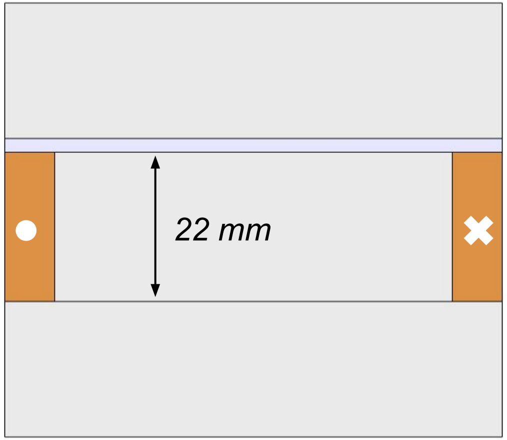
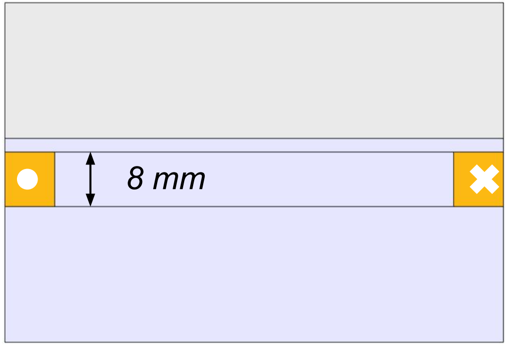


- Weight x2
- Higher losses to extract
- Armature reaction
- Stop the supply

Magnetization with SC coils:

Js = 400 A/mm²



- Highest torque/power density
- Low losses (with care)
- **Can be obtained at 60K**

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2- Superconductivity on the rotor side

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B_g_max: Air-gap flux density

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Magnetization with SC coils:

Js = 400 A/mm²

- Highest torque/power density
- Low losses (with care)
- **Can be obtained at 60K**

A fully SC motors:

- Interesting solution in the future: Reduction of the rotor volume and the use of iron
- BUT need reliable and lightweight rotating cryogeny at krpm level

The effort of ASCEND is on the development of AC coils and the extraction kW of losses at cryogenic temperature. Moreover, a partially SC motor on the AC side is the natural way to integrate it in the powertrain.

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3- Models and topologies

Model with components considering in the mass balance :

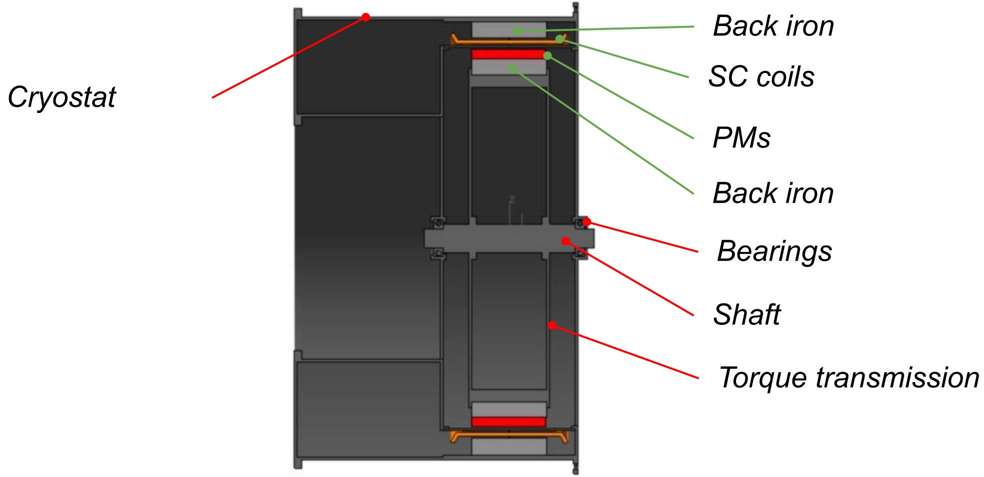


Fig. 5. Model considered for the mass balance

Two windings was investigated :

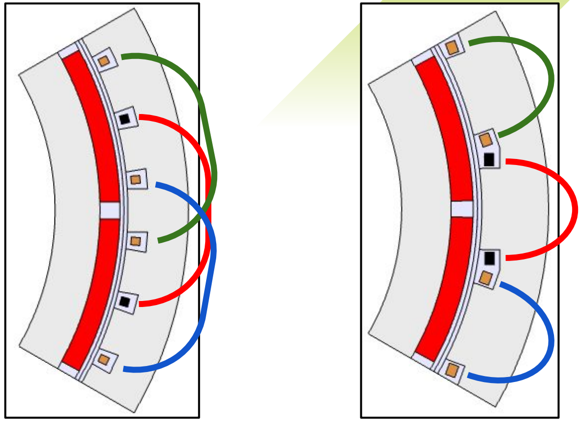
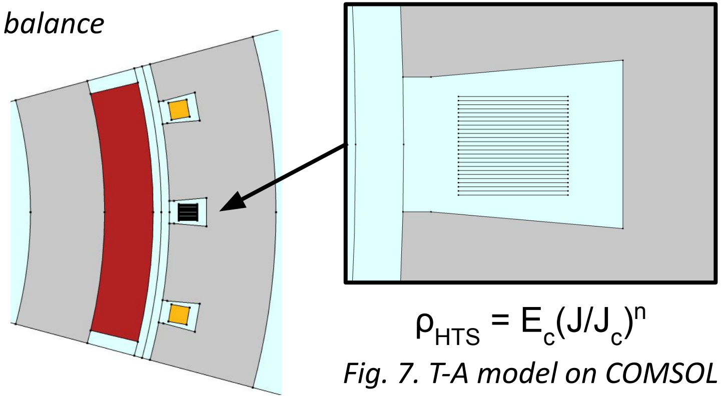


Fig. 6. Two types of armature winding considered

AC losses models :

2D T-A model



$$\rho_{HTS} = E_c(J/J_c)^n$$

Fig. 7. T-A model on COMSOL

3- Design of a 500 kW motor - MASS

Total mass vs Power factor (PF):

- Different aspect ratio of the motor was considered

  Asp_rat = 2 × R_g / L

  → No impact on the total mass

- With a target of the switched current < 1800 A (PF = 0.85)

  → **ToM ≅ 15 N.m/kg**

Assumptions: p = 6, Distributed winding

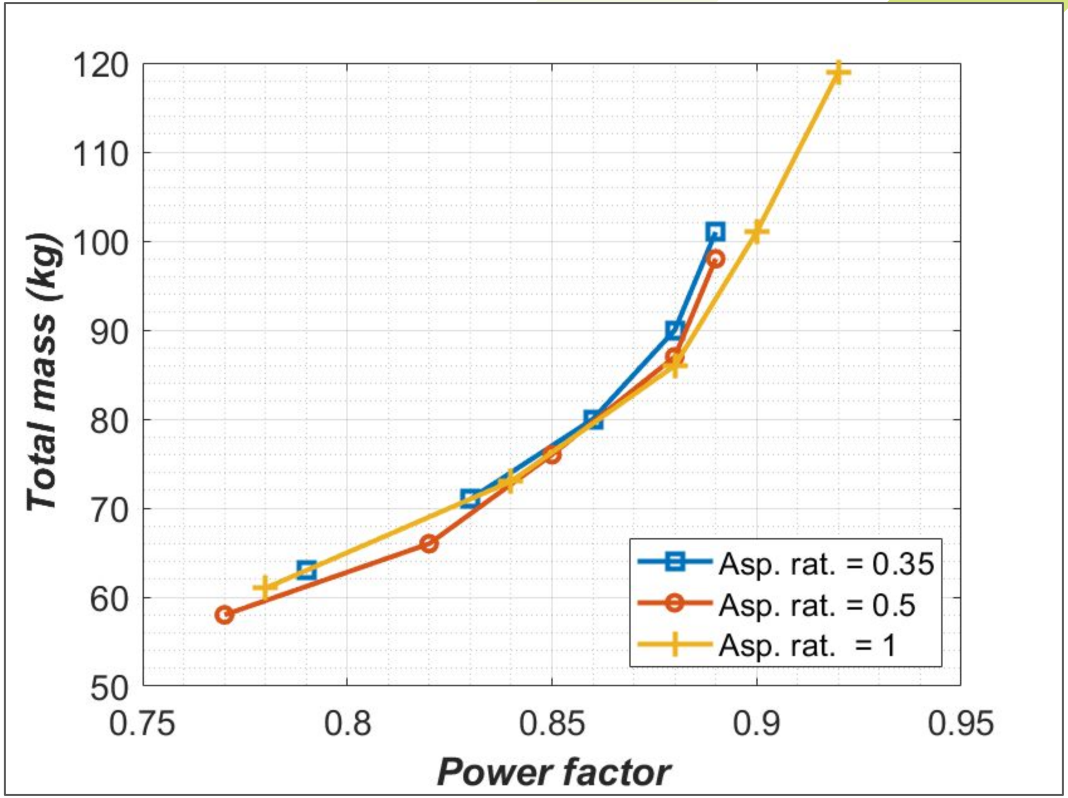


Fig. 8. Total mass of the 500 kW motor vs the PF

3- Design of a 500 kW motor - MASS

<u>Assumptions:</u> *p = 6, Distributed winding*

<u>Total mass vs Power factor:</u>

- Mass of the passive components could be up to **2x** time the mass of the active ones.

  → Cryostat = 24% of the total mass: **Increase the integration**

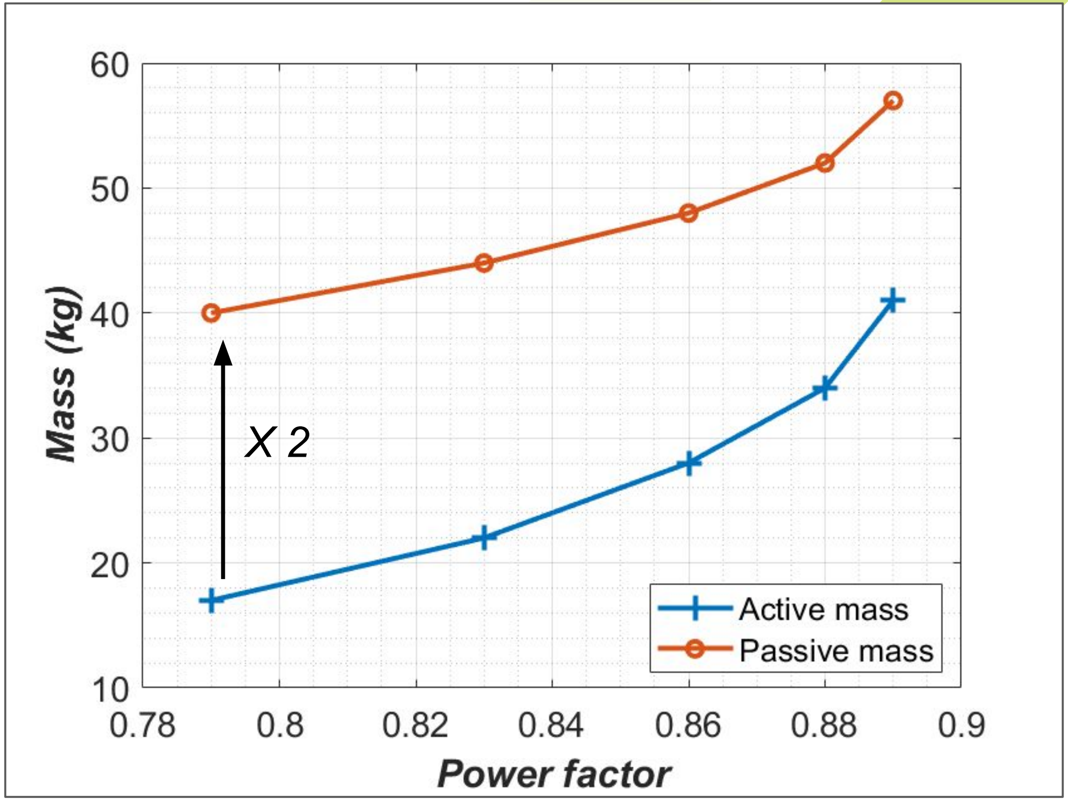


Fig. 9. Mass decomposition of the 500 kW motor vs the PF

3- Design of a 500 kW motor - MASS

Total mass vs poles pairs:

- **Distributed winding:**
  - **Significant weight reduction** p = 4 → 6: Active mass = Passive mass
  - **Less** from p = 6 → 8: Active mass << Passive
  - Crossing end-winding increase the complexity of the manufacturing process

Assumptions: *PF = 0.85*

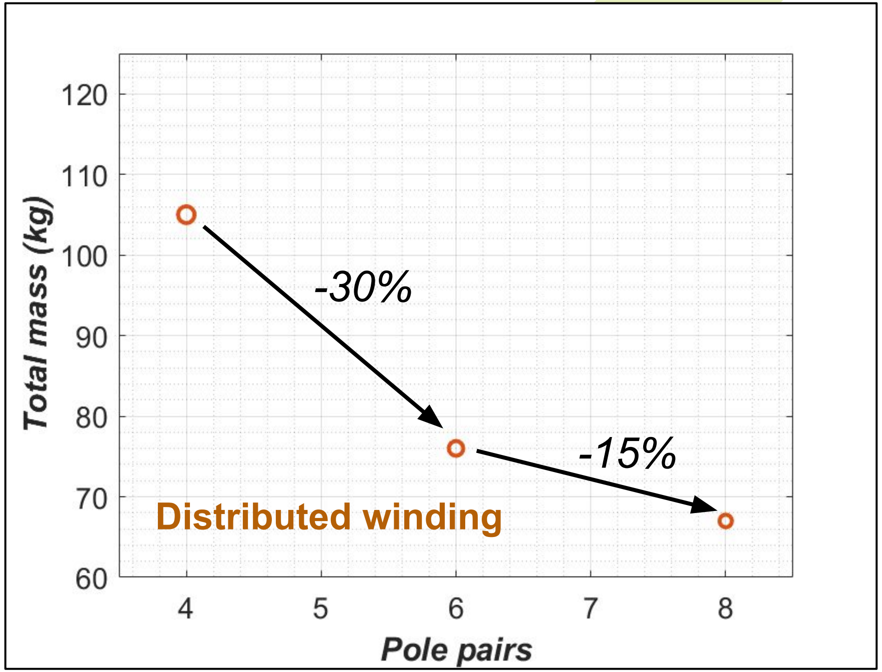


Fig. 10. Total mass of the 500 kW motor vs the pole pairs

3- Design of a 500 kW motor - MASS

Total mass vs poles pairs:

- **Concentrated winding:**
    - To fit with the switching current limit: the **configuration 18/12** has the smallest difference
    - Manufacturing easier

The **total mass are “comparable”** for a polarity of **6** for both type of winding.

Assumptions: *PF = 0.85*

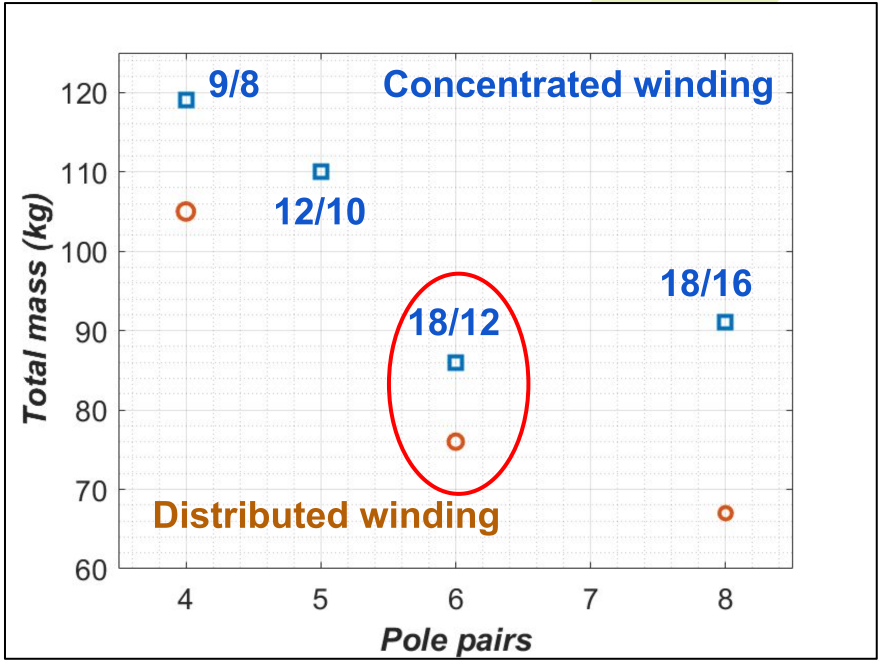


Fig. 10. Total mass of the 500 kW motor vs the pole pairs

3- Design of a 500 kW motor - LOSSES

Cryo. losses vs poles pairs:

- Not proportional to the pole pairs (electrical frequency)
- **Significant increase** of the cryo. losses between the distributed and concentrated winding
  - Double layer winding = +50% total slot current → Impact on Ic

Assumptions: *PF = 0.85*

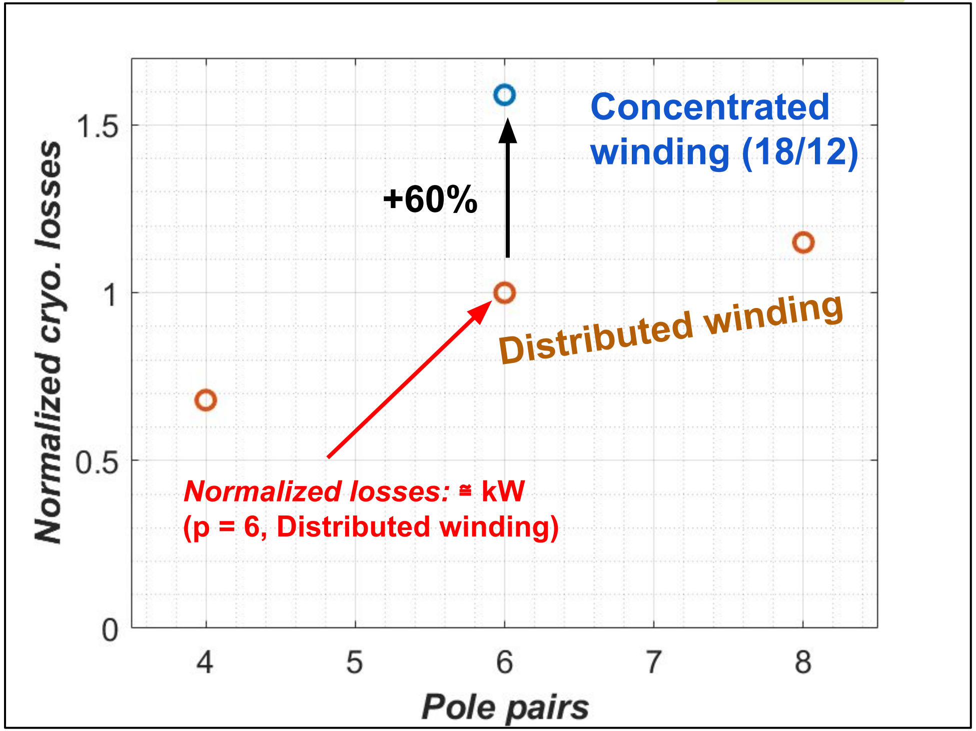


Fig. 12. Cryo. losses vs the poles pairs of the 500 kW motor

3- Design of a 500 kW motor - LOSSES

Cryo. losses vs Total mass:

- **The cryogenic losses** ↘ when **the Total mass** ↗ (also PF)

- The total efficiency of the motor is **constant** (PM eddy current + Iron losses ↗ when cryo. losses ↘)

Assumptions: *p = 6, Distributed winding*

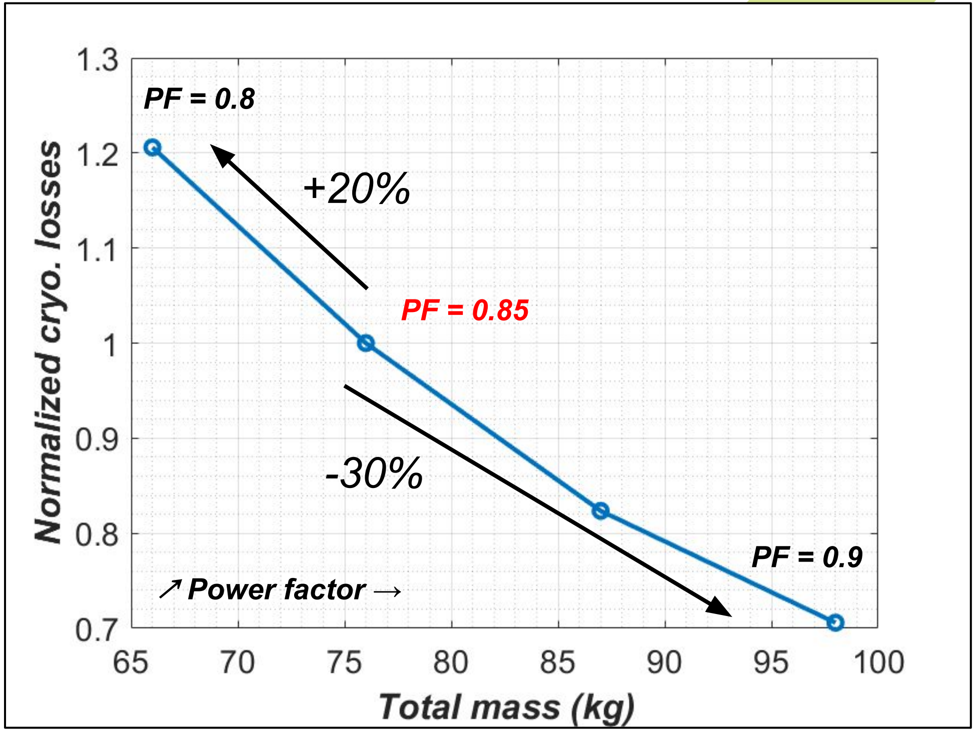


Fig. 11. Cryo. losses vs the total mass of the 500 kW motor

3- Design of a 500 kW motor

Assumptions: *p = 6, Distributed winding*

Parameters that impact the cryo. losses:

- **The number of slots:**

  Impact on the total slot current and on the slot magnetic field

  Potential ↘ **of 40%** by doubling the number of coils in the motor.

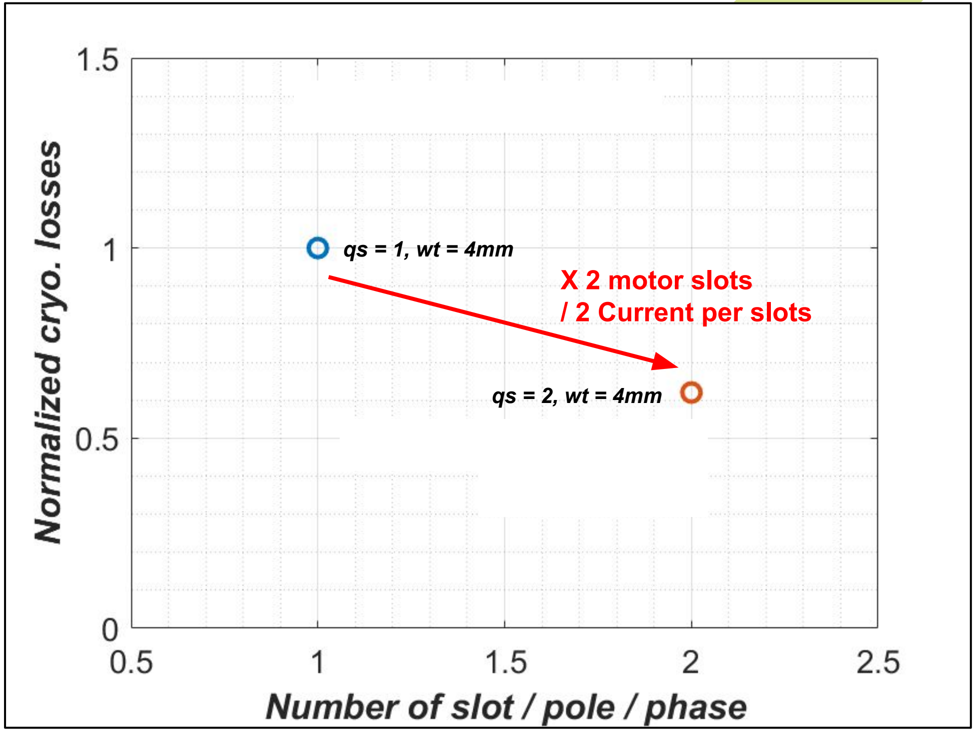


Fig. 13. Cryo. losses vs the number of slots of the 500 kW motor

3- Design of a 500 kW motor

<u>Parameters that impact the cryo. losses:</u>

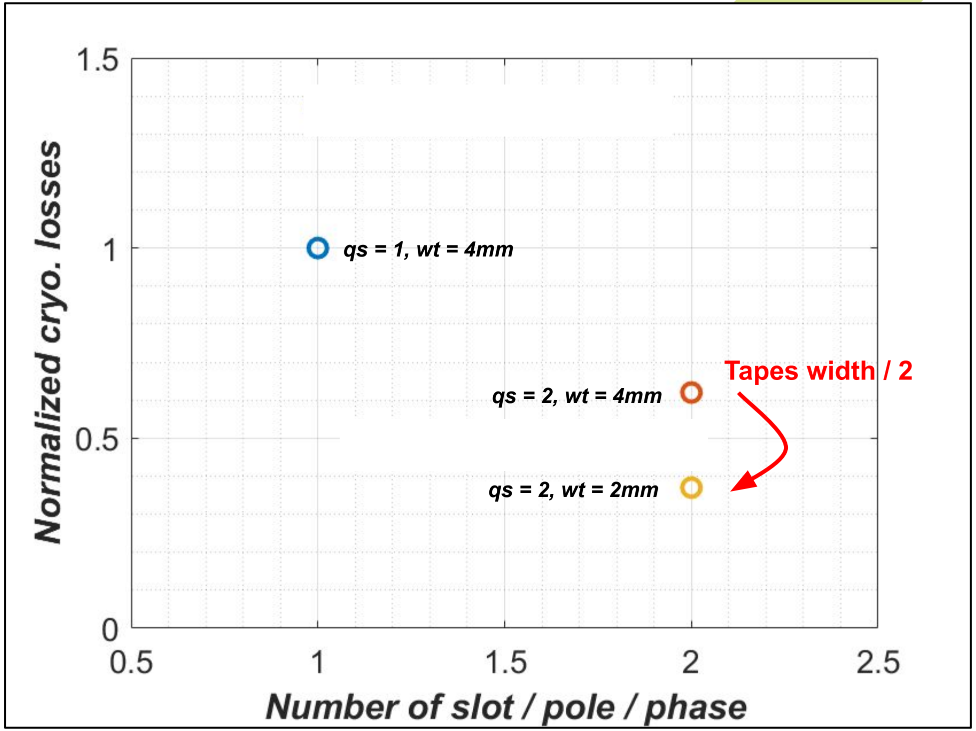
- **The number of slots:**

  Impact on the total slot current and on the slot magnetic field

  Potential ↘ **of 40%** by doubling the number of coils in the motor.

- **The width of the HTS tapes:**

  Potential ↘ **of 60%** with a single layer of 2 mm tape



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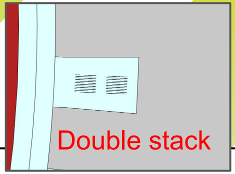
3- Design of a 500 kW motor



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  Potential ↘ **of 60%** with a single layer of 2 mm tape

If geometry constraints (too small slot width) with the required number of tapes → double stack of 2 mm = potential ↘ **of 50%**... But not always !

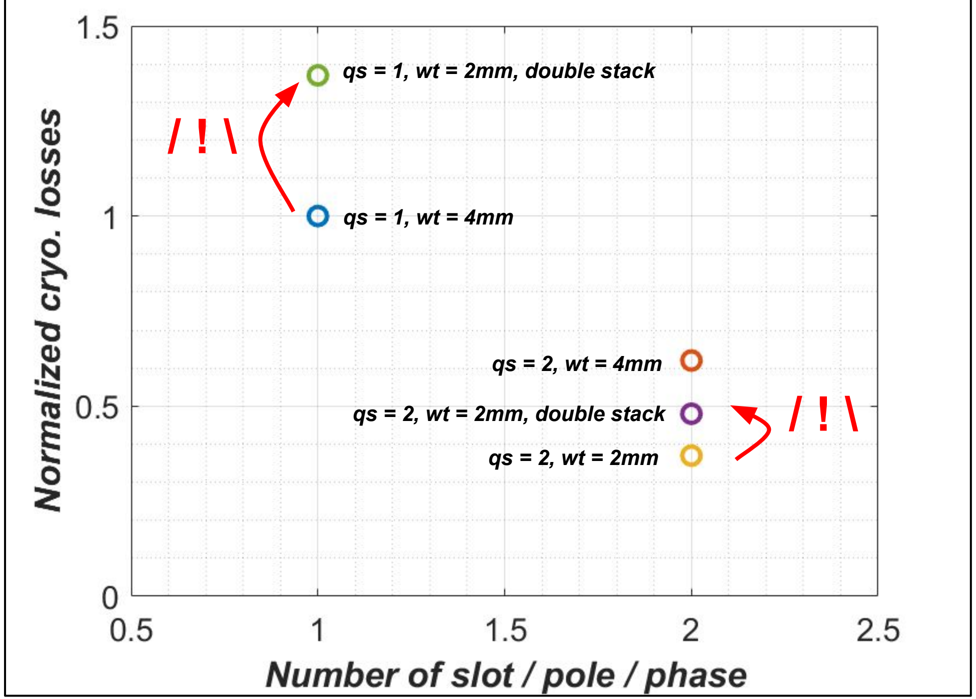

Fig. 13. Cryo. losses vs the number of slots of the 500 kW motor

3- **Extrapolation to MW-class application**

Extrapolation to MW-class application:

- **Based on the assumptions:**
  - Limit the polarity to **6** → **500 Hz**
  - Switching current of **1800 A** → **PF ≅ 0.85**
  - Consequent space for coils interconnexion
  - Stainless steel cryostat
  - Coils made with **4 mm** width tape

→ **Performances that can be obtained today**

- **Results:**
  - **X 4** on the Power = **X 3** on the losses
  - Today torque density = **20 N.m/kg**
  - …BUT **+75%** with **2 mm** tape, **9** pole pairs, **PF = 0.8** and passive component optimization (Ludovic's presentation)

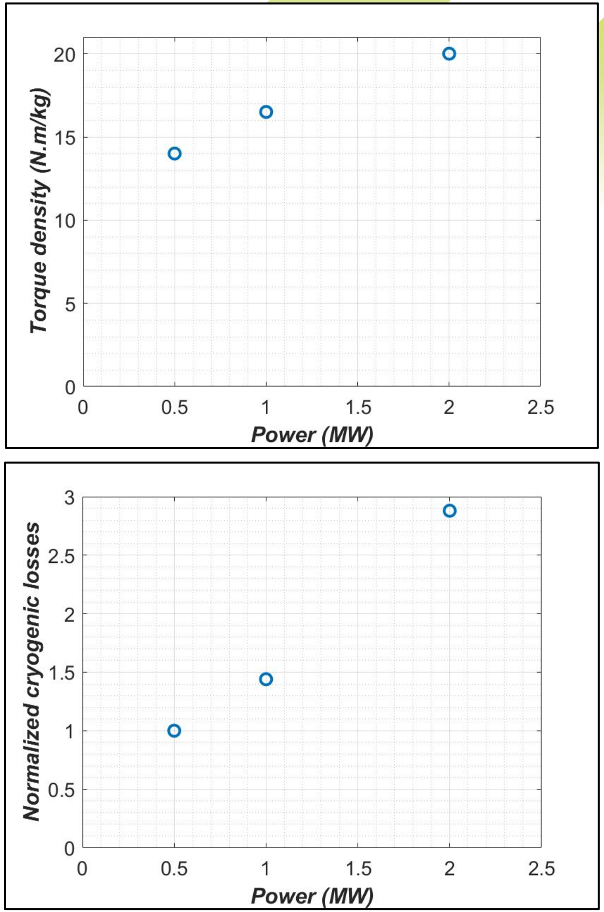

Fig. 14. Extrapolation to higher power

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Conclusion

- A partial SC motor with SC on the stator side shows good **torque density / efficiency** if:
  - Distributed winding > Concentrated winding
  - Optimal point between the PF and the mass

- With the **TODAY** technologies, the performances at **2 MW / 5 krpm** could reach:
  - Performances of **10,5 kW/kg** & **20 N.m/kg**
  - **> 99.4 %** of efficiency

- Next step to increase motor performances to be one day integrated in a aircraft:
  - Optimization of the **passive component**
  - **2 mm width tape** to reduce the AC losses in superconductors
  - Superconducting rotor ???

- This study presents one scenario of a motor at 5 krpm → Direct drive or High speed + Gear box is also investigated for the powertrain optimum (cables, power electronics, cooling system, …)