AC loss modeling of the stator of a 1 MW REBCO superconducting motor for aviation

E Pardo, A Ghabeli

F Grilli

E Berberich, S Wolftaedler, T Reis

ELÚ

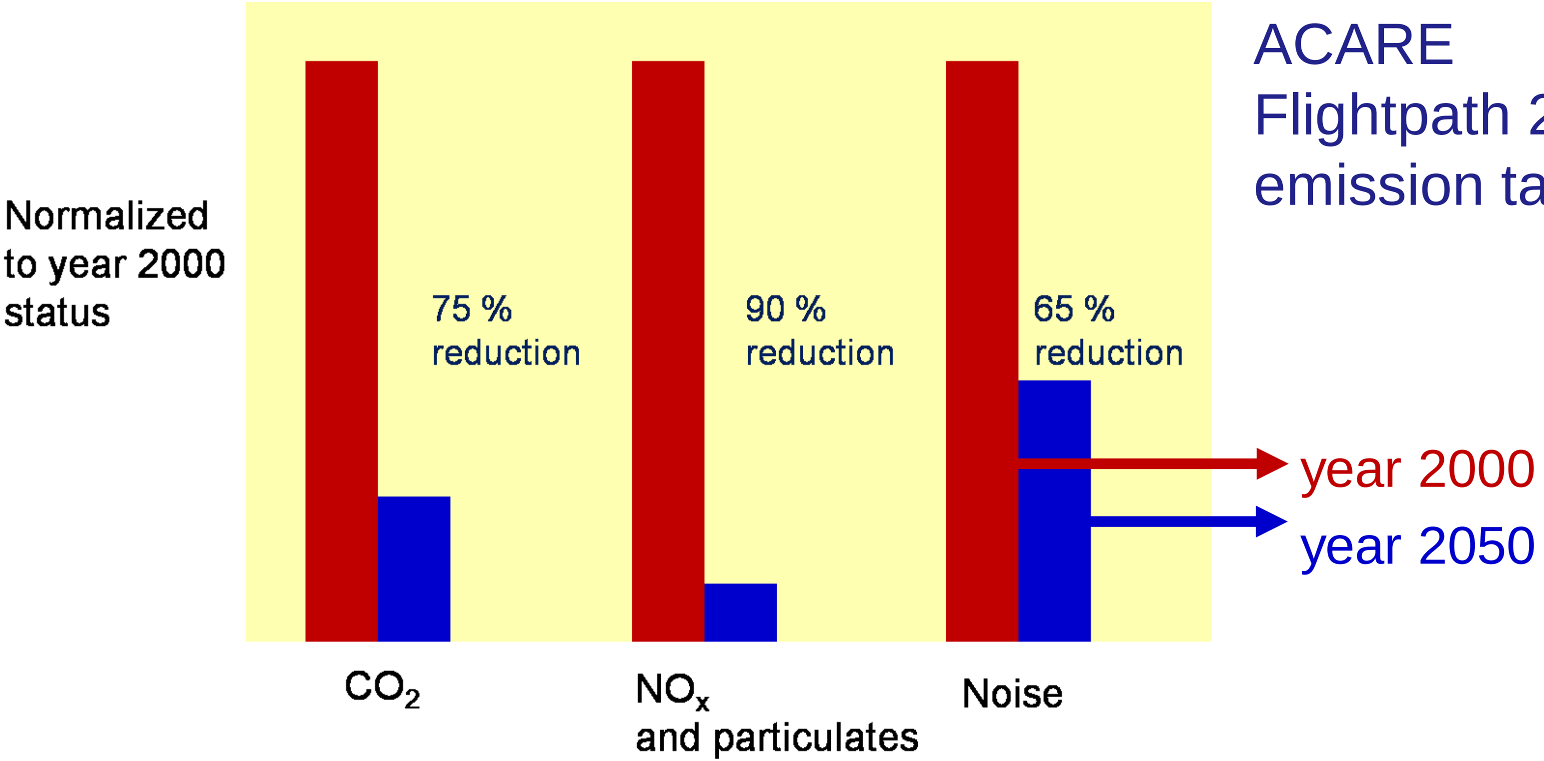
Karlsruhe Institute of Technology

OSWALD

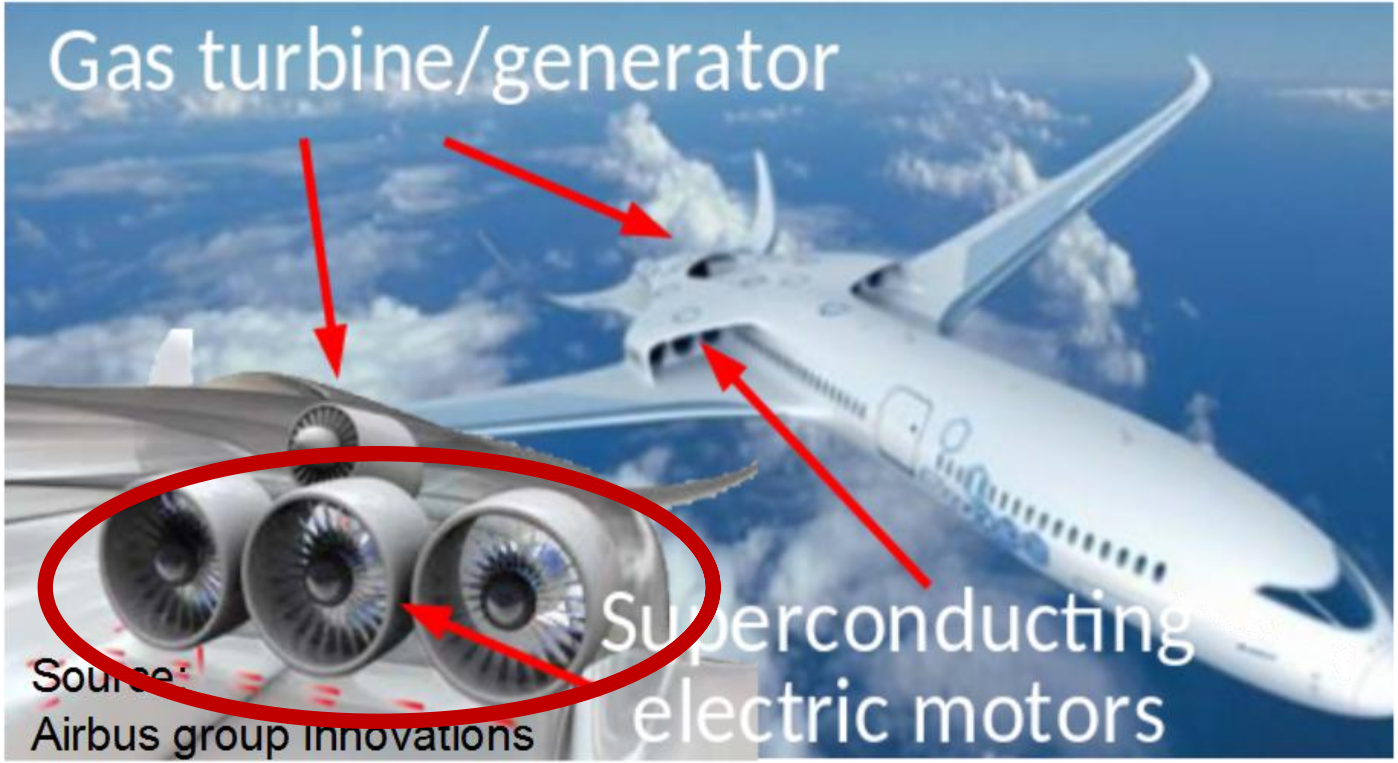
The European Union wants to reduce emissions

Drastic reductions need drastic improvements

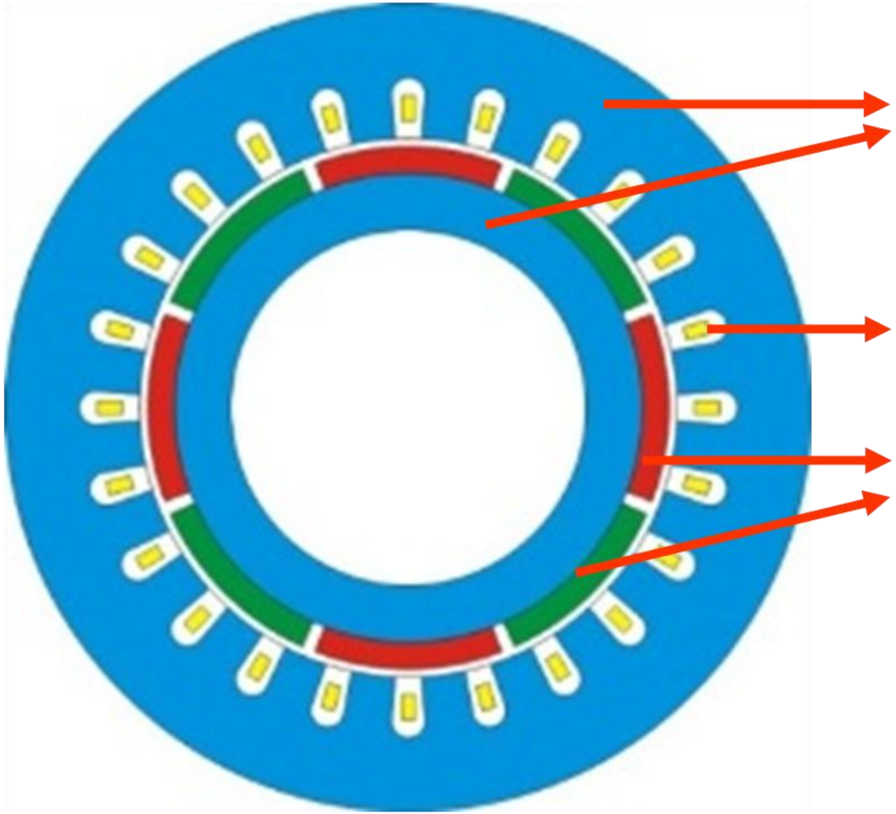
ACARE
Flightpath 2050
emission targets



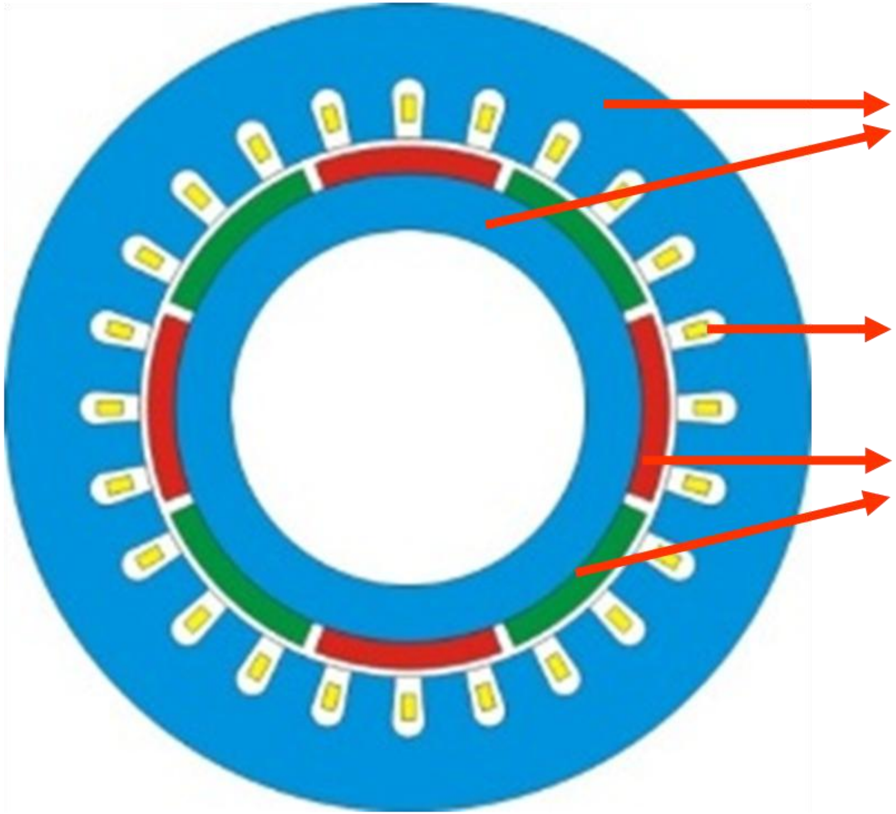
Hybrid electric airplane can reduce emissions



Superconducting motor



Full superconducting motor



Iron

Superconducting stator

Superconducting magnets or coils

AC loss modeling of the stator of a 1 MW REBCO superconducting motor for aviation

E Pardo, A Ghabeli

F Grilli

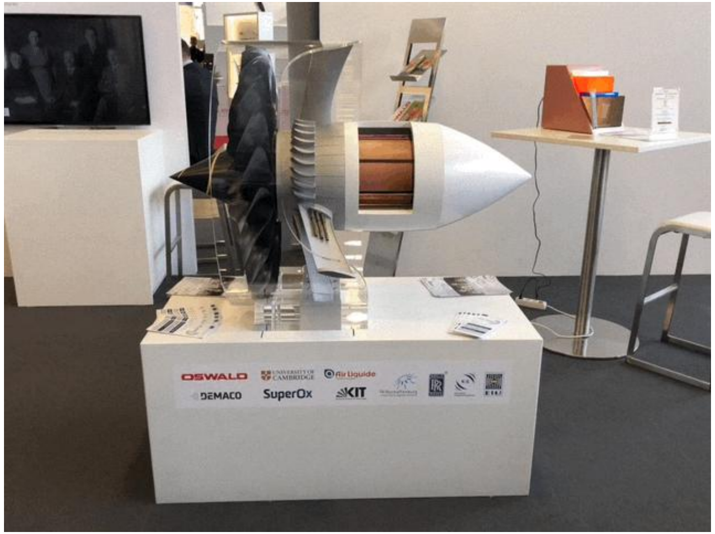
E Berberich, S Wolftaedler, T Reis

ELÚ

Karlsruhe Institute of Technology

OSWALD

Advanced Superconductor Motor Demonstrator (ASuMED)



ASuMED

OSWALD
UNIVERSITY OF CAMBRIDGE
Air Liquide
creative oxygen
KIT
Karlsruhe Institute of Technology
K·S
ELÚ
Rolls-Royce
DEMACO
SuperOx
hochschule aschaffenburg
university of applied sciences

Our work continues with national funding

We acknowledge the grants:

APVV Grant no. APVV-19-0536
VEGA Grant no. 2/0097/18

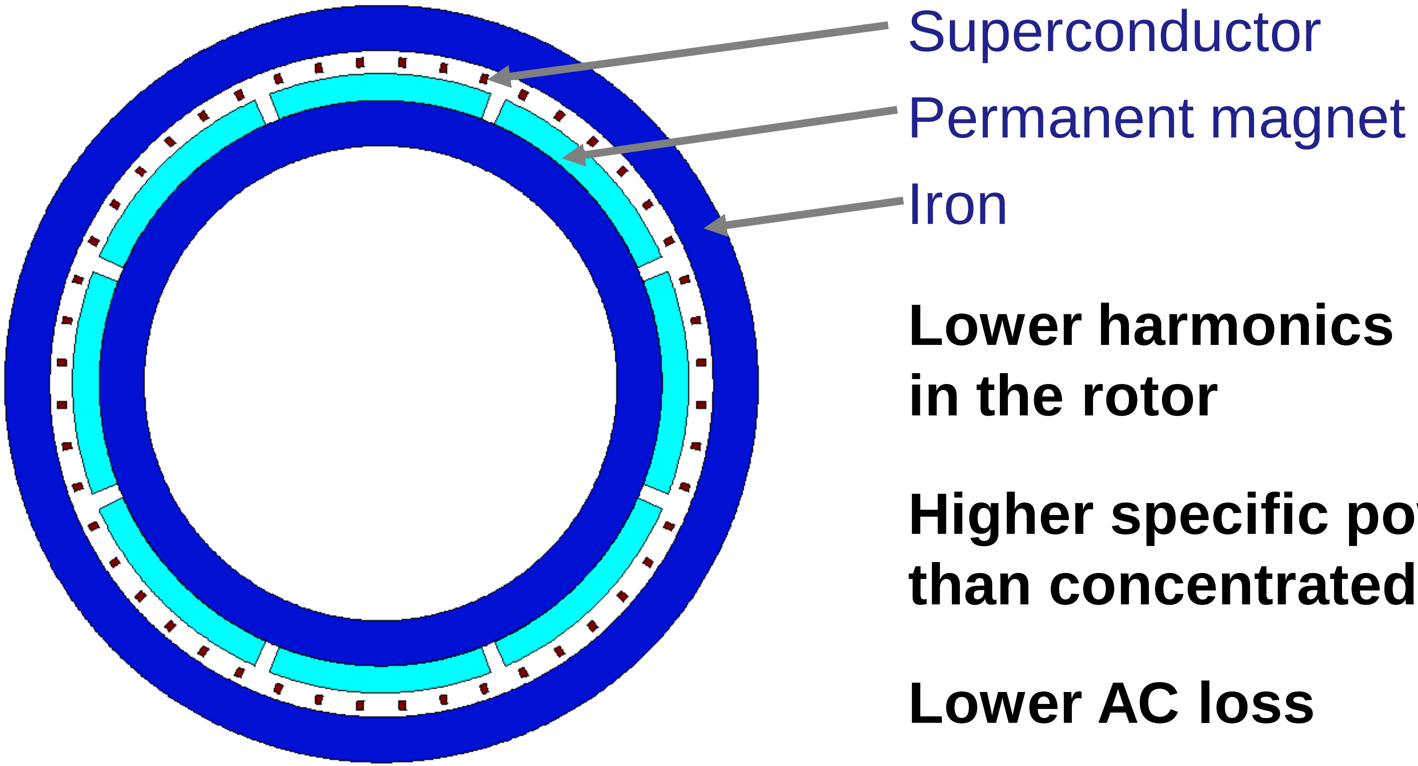
Stator

Flux pump

Distributed winding

ASuMED

Funded by the European Commission Grant No 723119



Lower harmonics in the rotor

Higher specific power than concentrated windings

Lower AC loss

Stator

- Combined method
- Conceptual study
- Final stator results
- Single method for the full motor

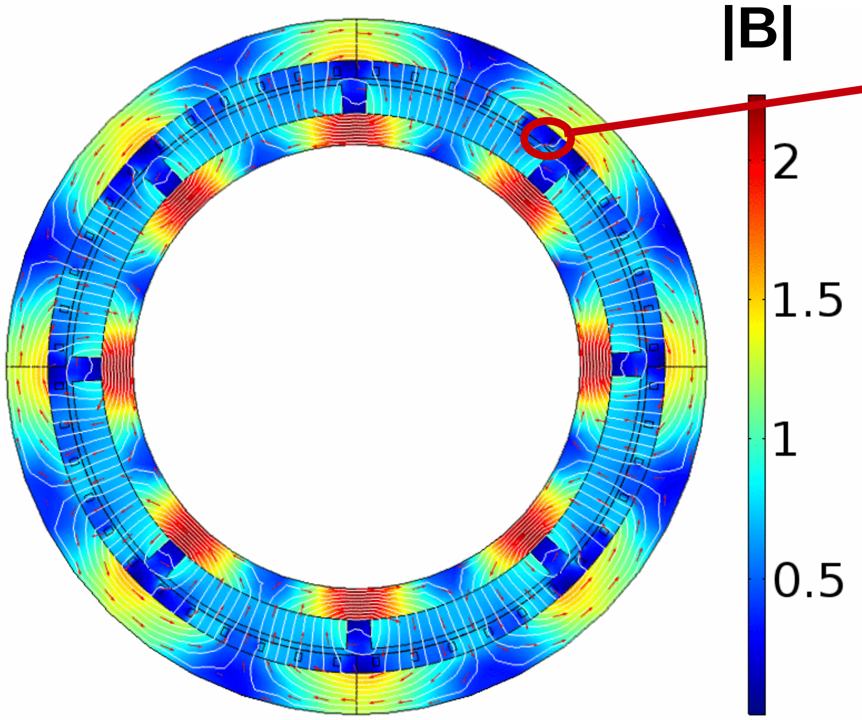
Flux pump

Stator

- Combined method
- Conceptual study
- Final stator results
- Single method for the full motor

Flux pump

Conventional static Finite Element Method



Current density assumed uniform in coils

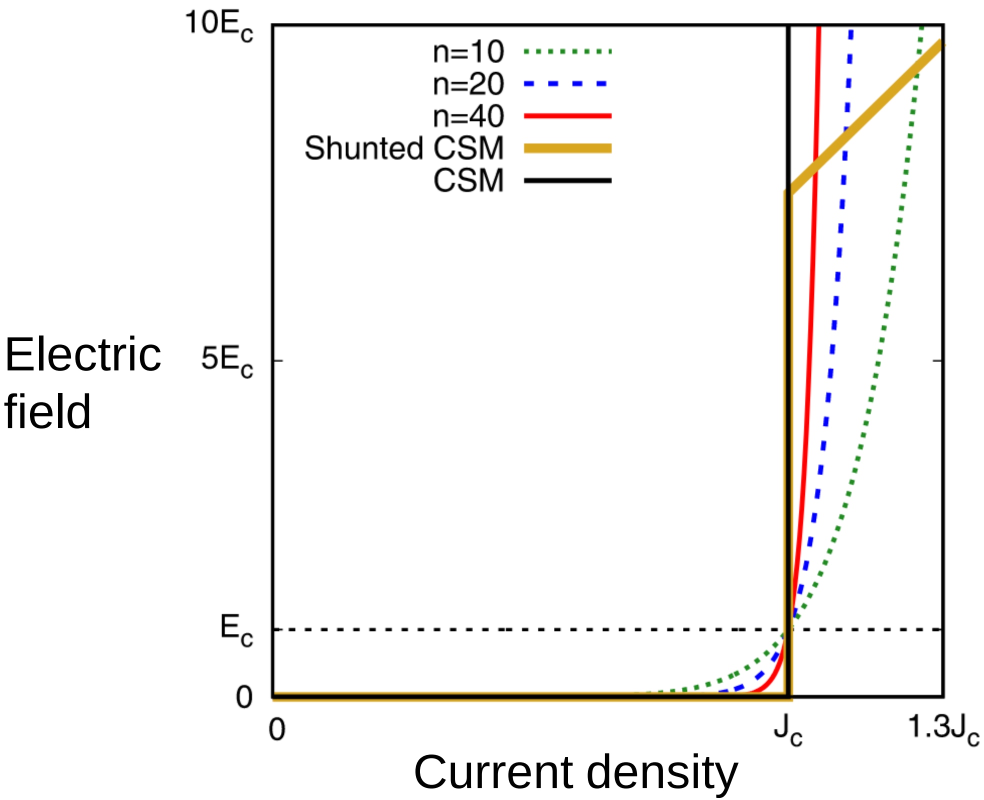
$$\nabla \times (\nabla \times \mathbf{A}) = \mu \mathbf{J}$$

$$\mathbf{B} = \nabla \times \mathbf{A}$$

We need another method to calulate AC loss in superconductor

Superconductor resistivity is highly non-linear

Funded by the European Commission Grant No 723119



Flux-creep relation

$$\mathbf{E}(\mathbf{J}) = E_c \left(\frac{|\mathbf{J}|}{J_c} \right)^n \frac{\mathbf{J}}{|\mathbf{J}|}$$

Minimum Electro Magnetic Entropy Production (MEMEP)

Funded by the European Commission Grant No 723119

Solving the equations

$$\mathbf{E}(\mathbf{J}) = -\frac{\Delta \mathbf{A}}{\Delta t} - \nabla\phi \qquad\qquad \nabla\cdot\mathbf{J} = 0$$

is the same as minimizing the functional

J change between two time instants

$$L = \int_V \mathrm{d}V \left[\frac{1}{2}\Delta\mathbf{J}\cdot\frac{\Delta\mathbf{A}_J}{\Delta t} + \Delta\mathbf{J}\cdot\frac{\Delta\mathbf{A}_a}{\Delta t} + U(\mathbf{J}) + \nabla\phi\cdot\mathbf{J}\right]$$

Non-linear **E**(**J**) relation

$$U(\mathbf{J}) = \int_0^{\mathbf{J}} \mathrm{d}\mathbf{J}'\cdot\mathbf{E}(\mathbf{J})'$$

E Pardo, M Kapolka 2017 J Comp. Phys.

Combined method

Funded by the European Commission Grant No 723119

FEM calculates background vector potential

Assumed uniform **J** in superconductor

→

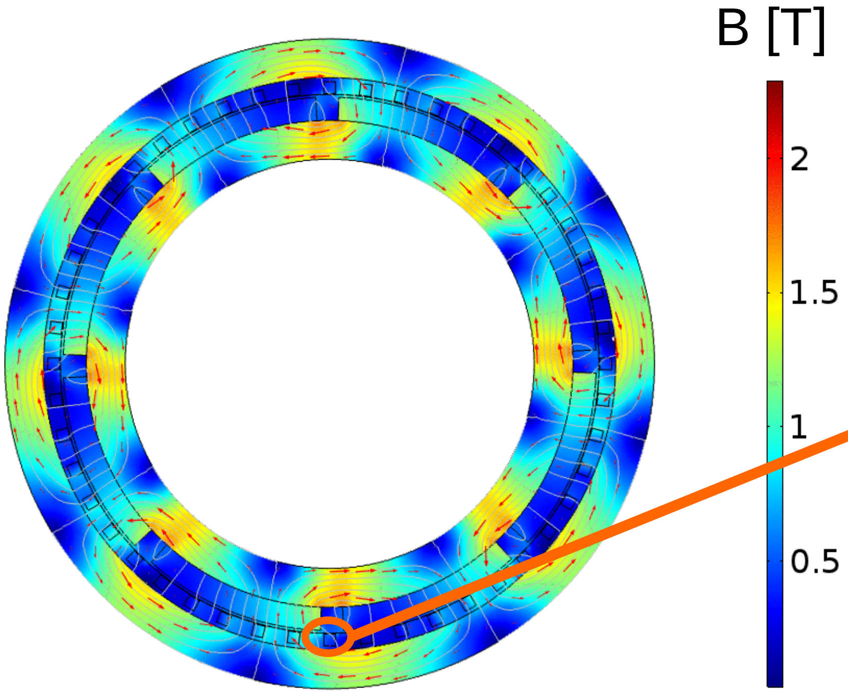
MEMEP calculates non-uniform **J** and AC loss

Fast method

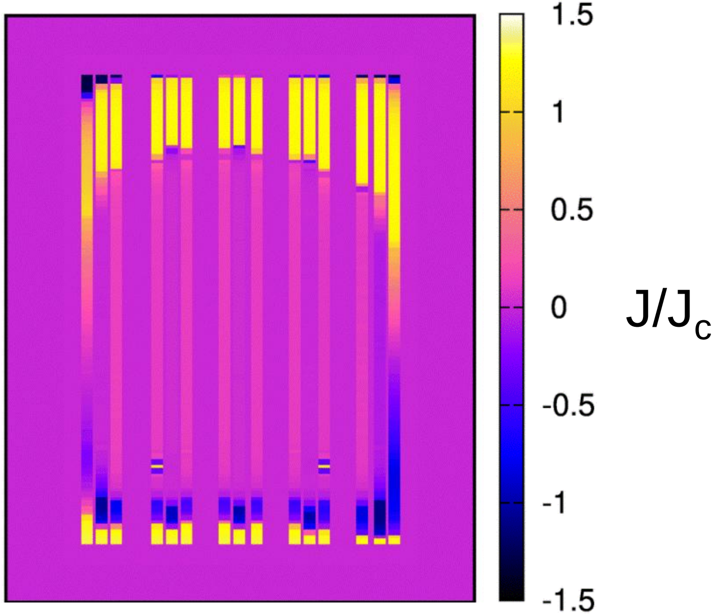
Ideal to optimize the superconductor windings

MEMEP calculates non-linear eddy currents and AC loss

Funded by the European Commission Grant No 723119



more than 1000 tapes



E. Pardo et al. 2019 IEEE TAS

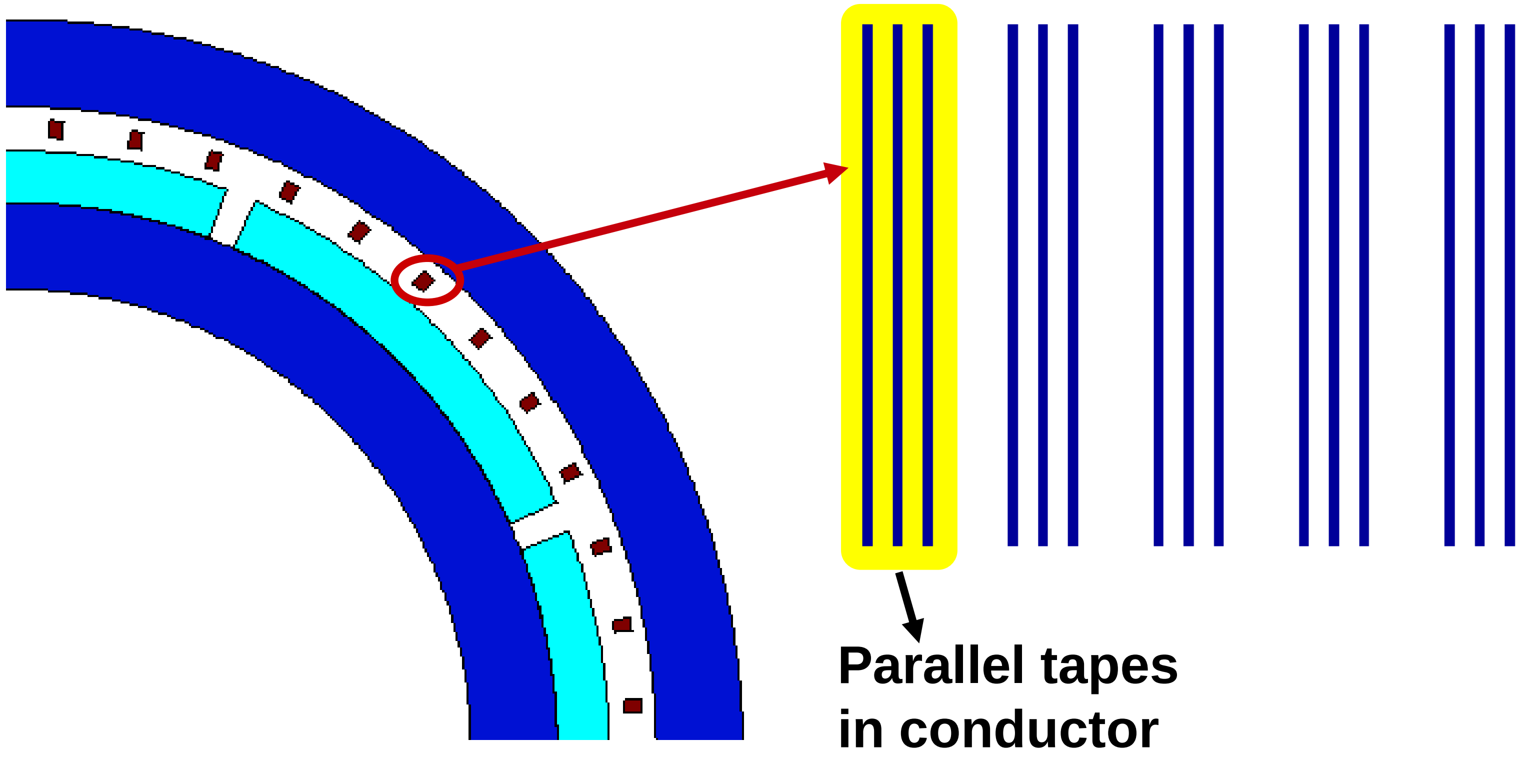
Modelling

- Combined method
- Conceptual study
- Final stator results
- Single method for the full motor

Measurement

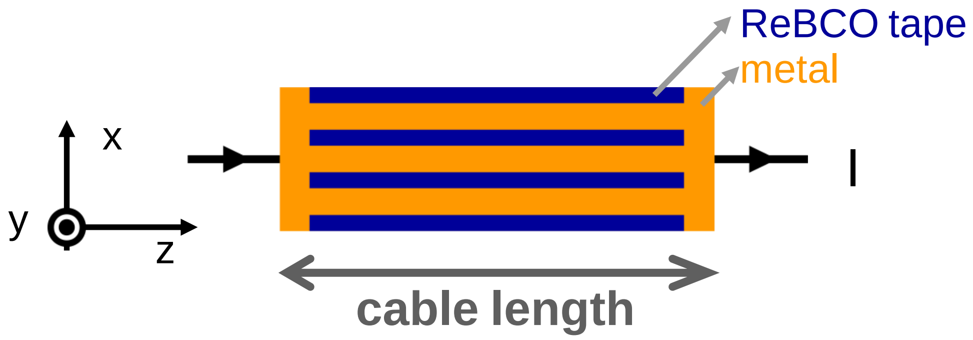
Base cross-section:
3-tape conductor

Funded by the
European Commission
Grant No 723119



Coupling configurations

Coupled



Coupled at ends

Uncoupled

Here, we assume zero resistivity in metal

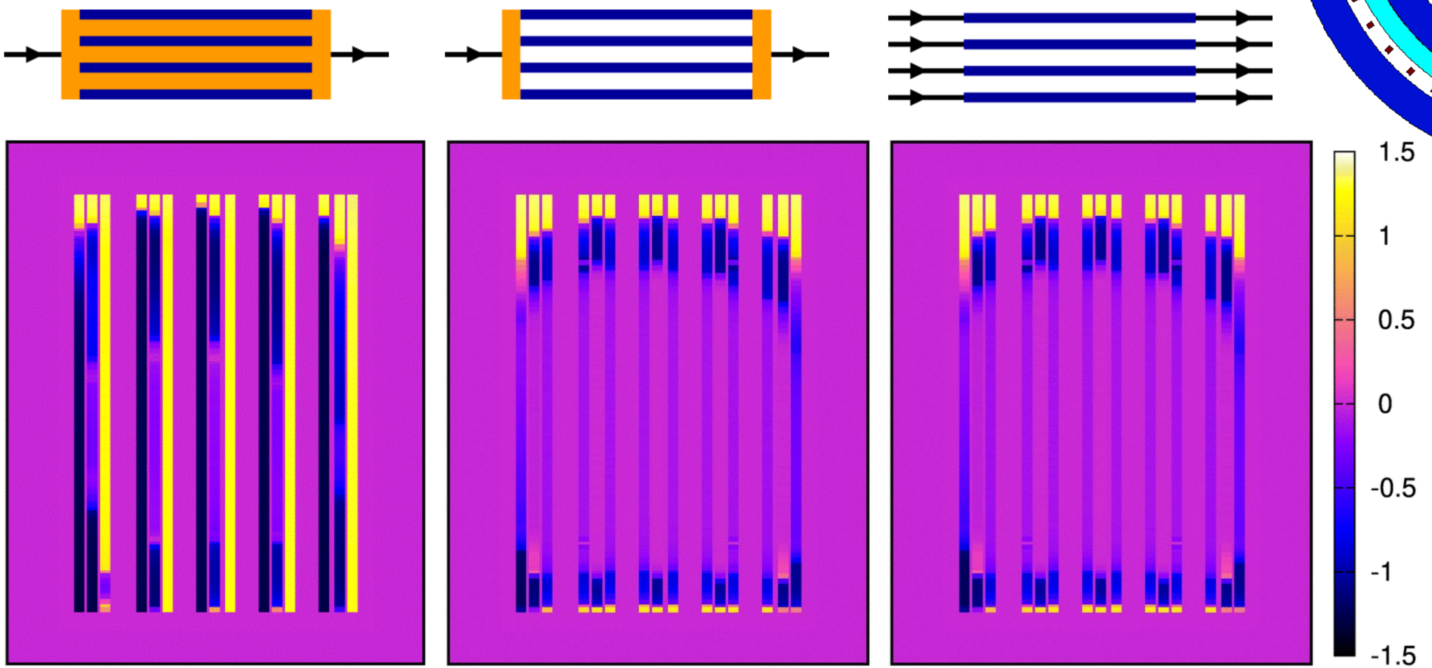
We can also use realistic resistivity

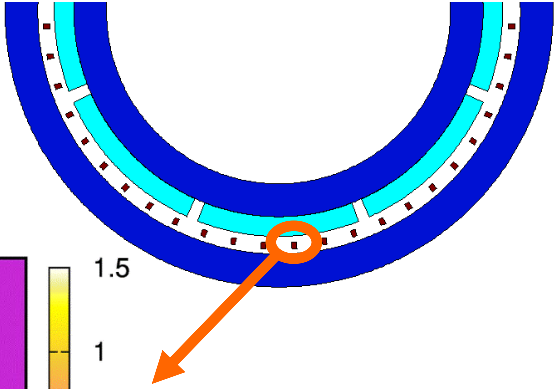
[S Li, et al. 2020 SuST]

Coupling configuration changes superconductor currents

Funded by the
European Commission
Grant No 723119

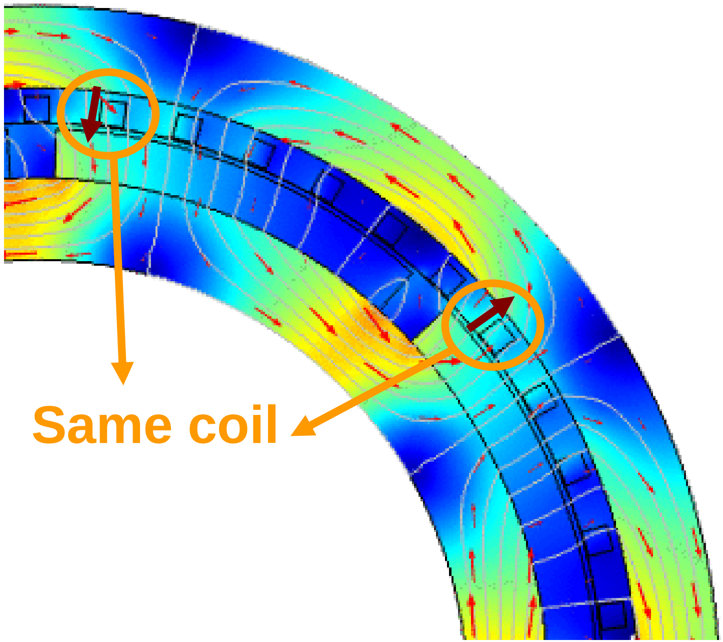
Coupled | Coupled at ends | Uncoupled

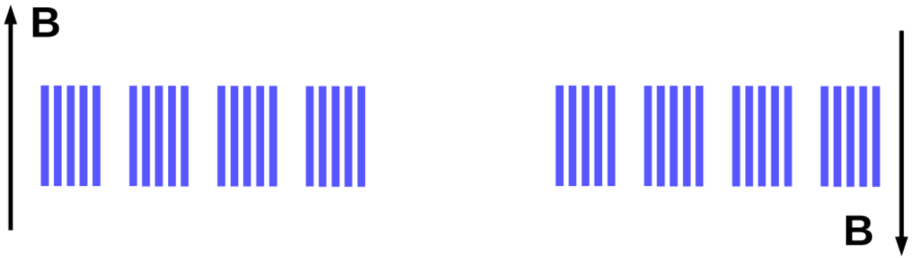




Self-transposition effect

Funded by the European Commission Grant No 723119



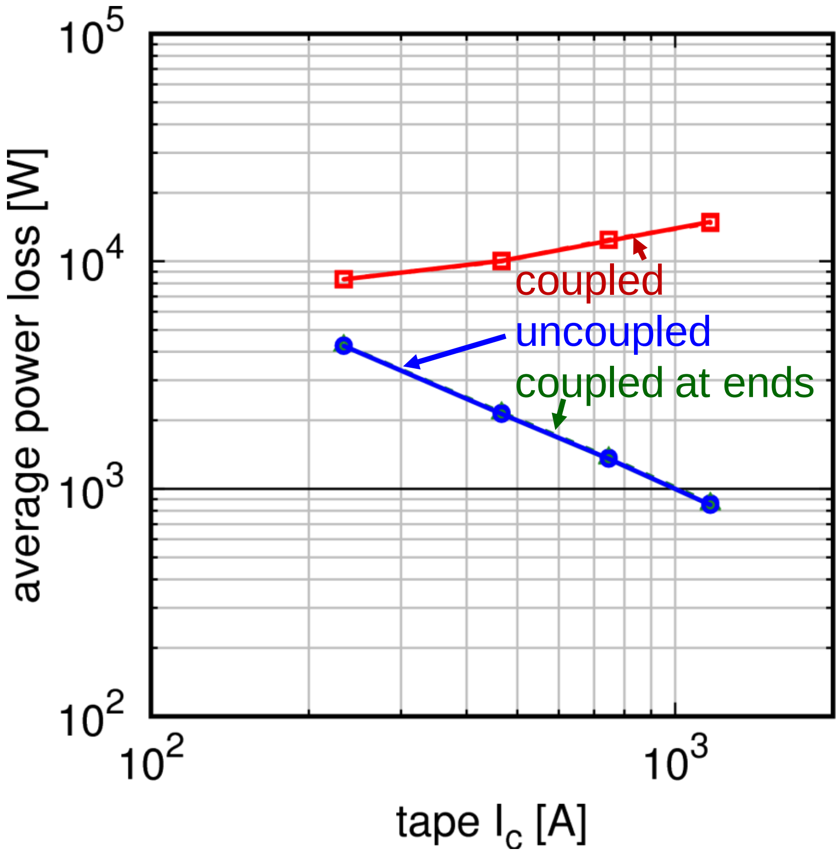


The magnetic flux between tapes cancels thanks to symmetry

No need of transposition to reduce AC loss

Coupled at ends is the same as uncoupled

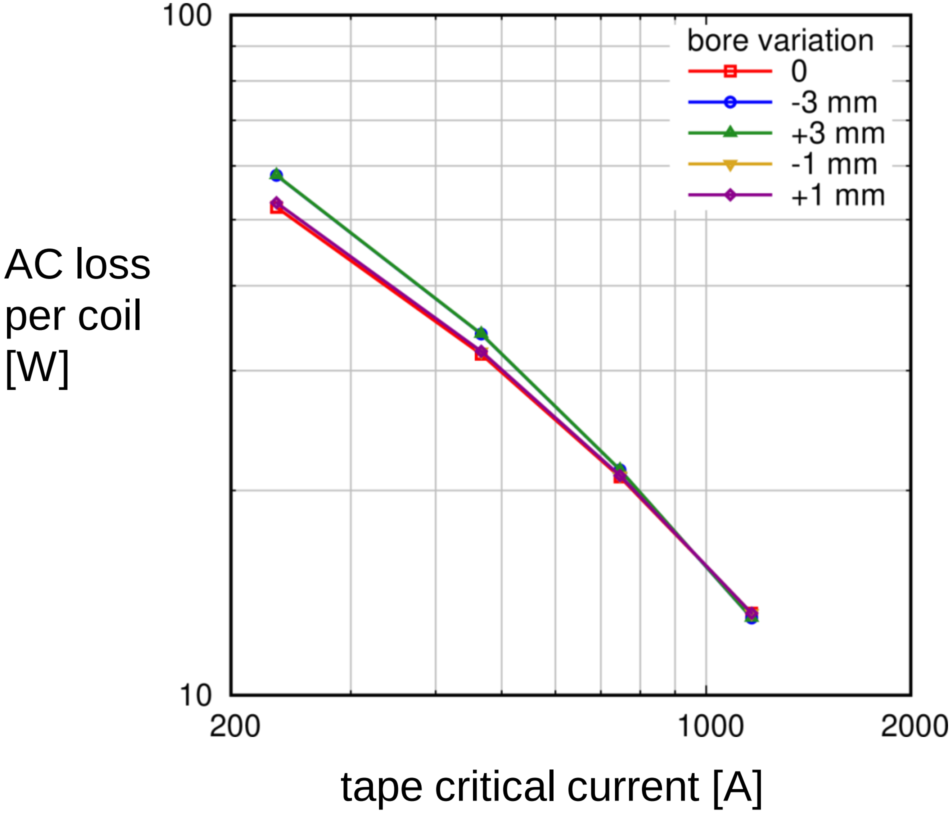
Funded by the European Commission Grant No 723119



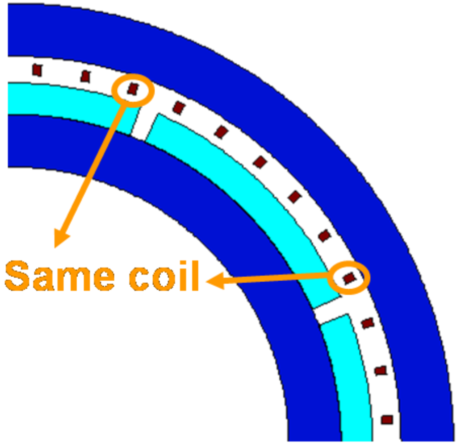
Self-transposition effect reduces AC loss

AC loss is not sensitive to stator coil imperfections

Funded by the European Commission Grant No 723119



We change the bore size of one coil

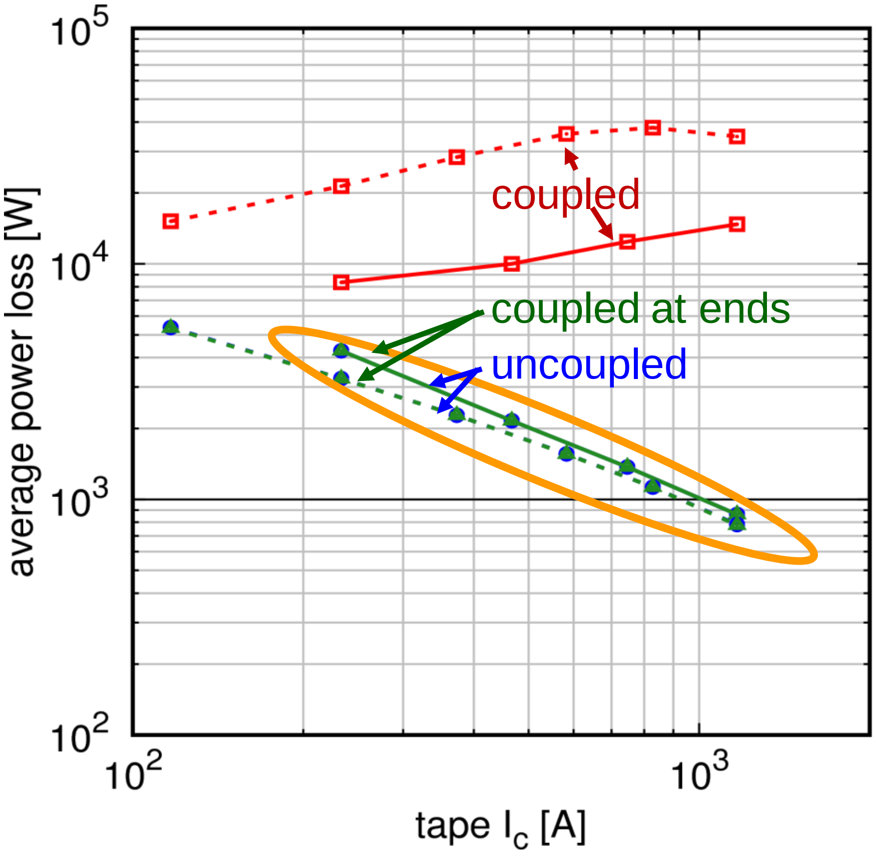


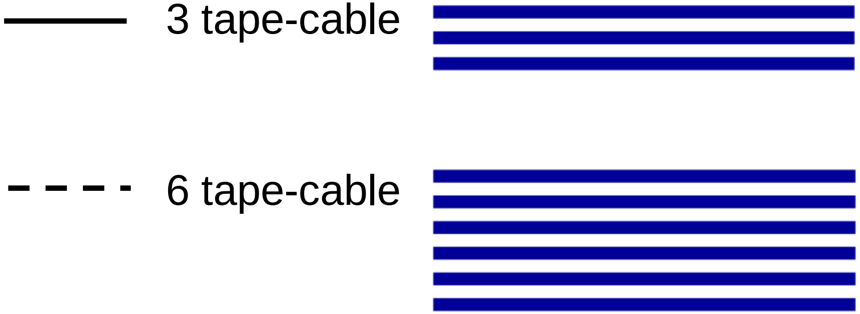
Up to 1 mm error in bore size does not have impact

Case of 3-tape conductor with no load

Increasing number of tapes in conductor reduces AC loss

Funded by the European Commission Grant No 723119



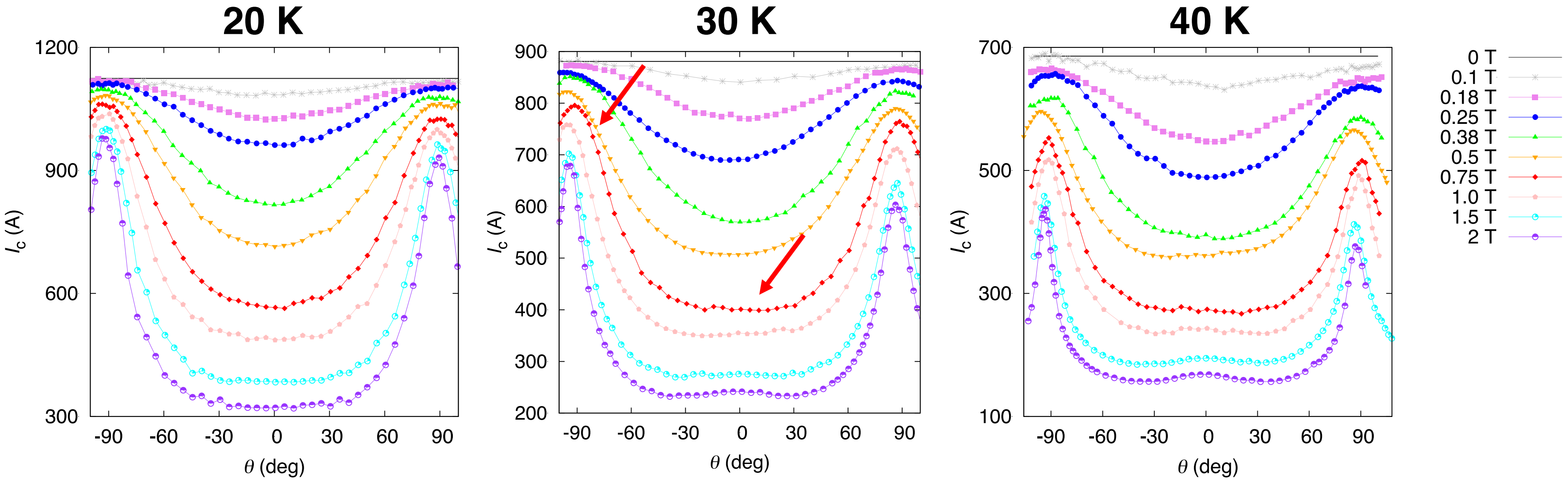


Cause:

main AC loss due to perpendicular flux to tape

Measured Jc(B,T) dependence

Funded by the
European Commission
Grant No 723119



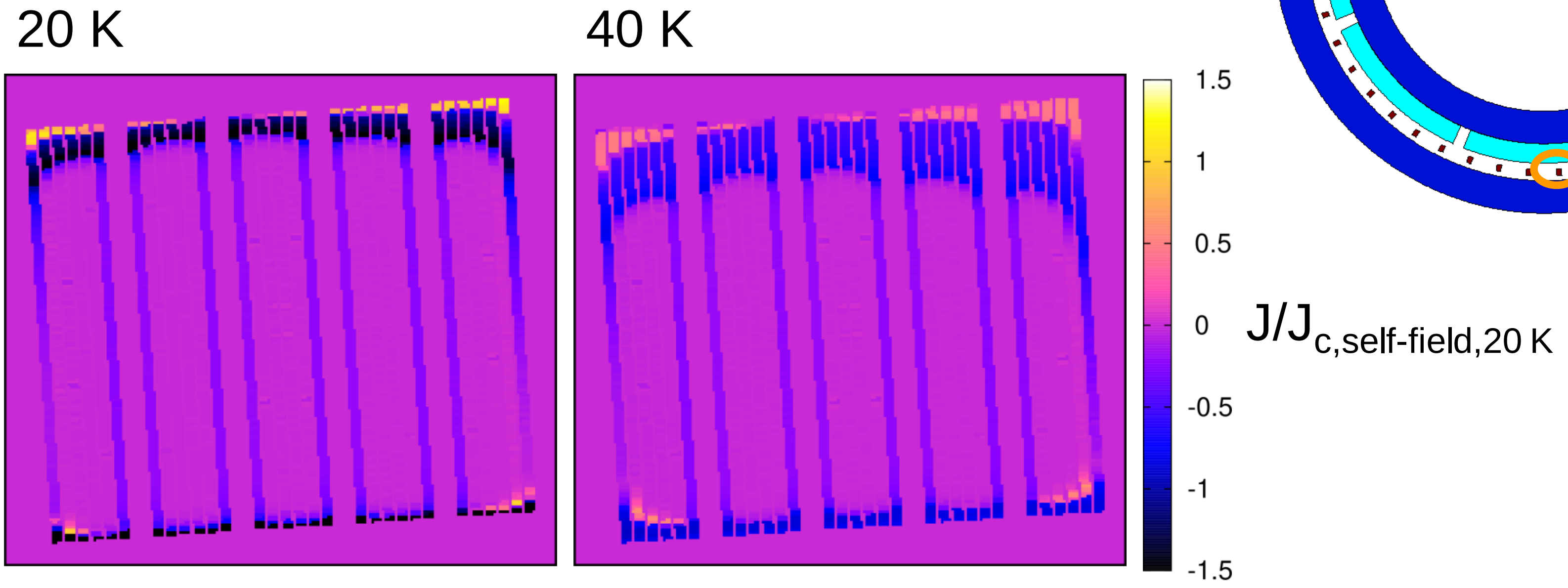
J_c(B) measured at several temperatures at KIT

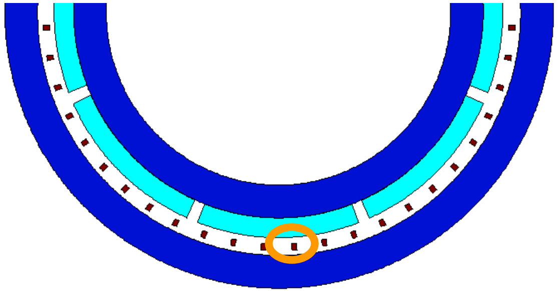
We interpolate J_c(B) for intermediate temperatures.

4 mm wide SuperOx tape

Current penetration increases with temperature

Funded by the European Commission Grant No 723119

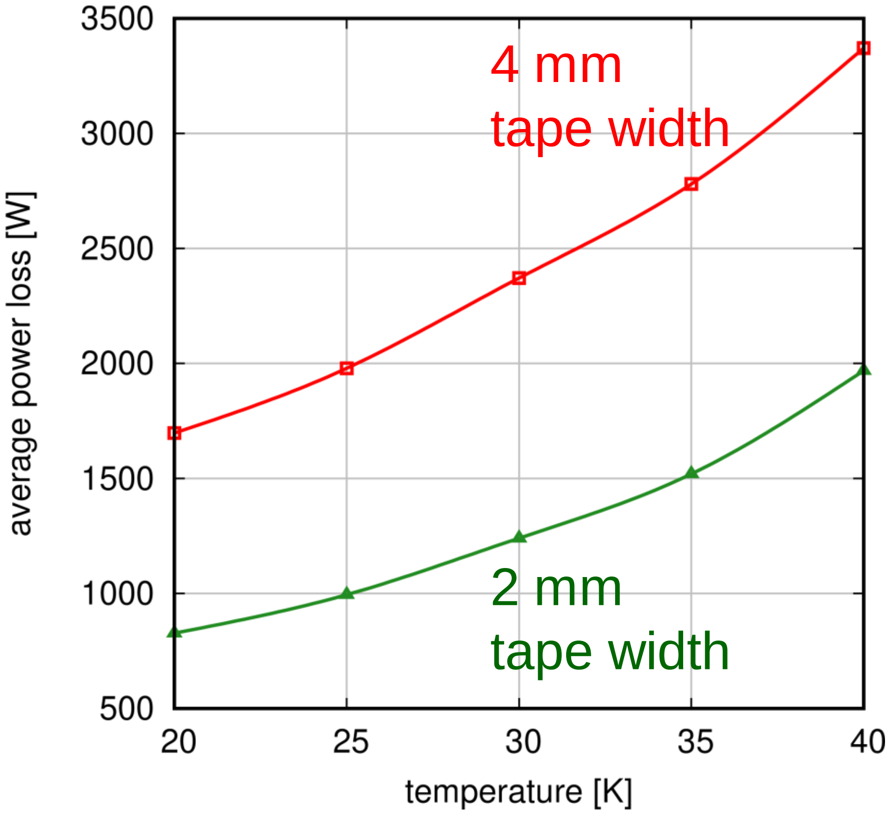




Current density at a particular time step

Narrower tapes decrease AC loss

Funded by the
European Commission
Grant No 723119



Narrower tapes with the same J_c are very interesting!

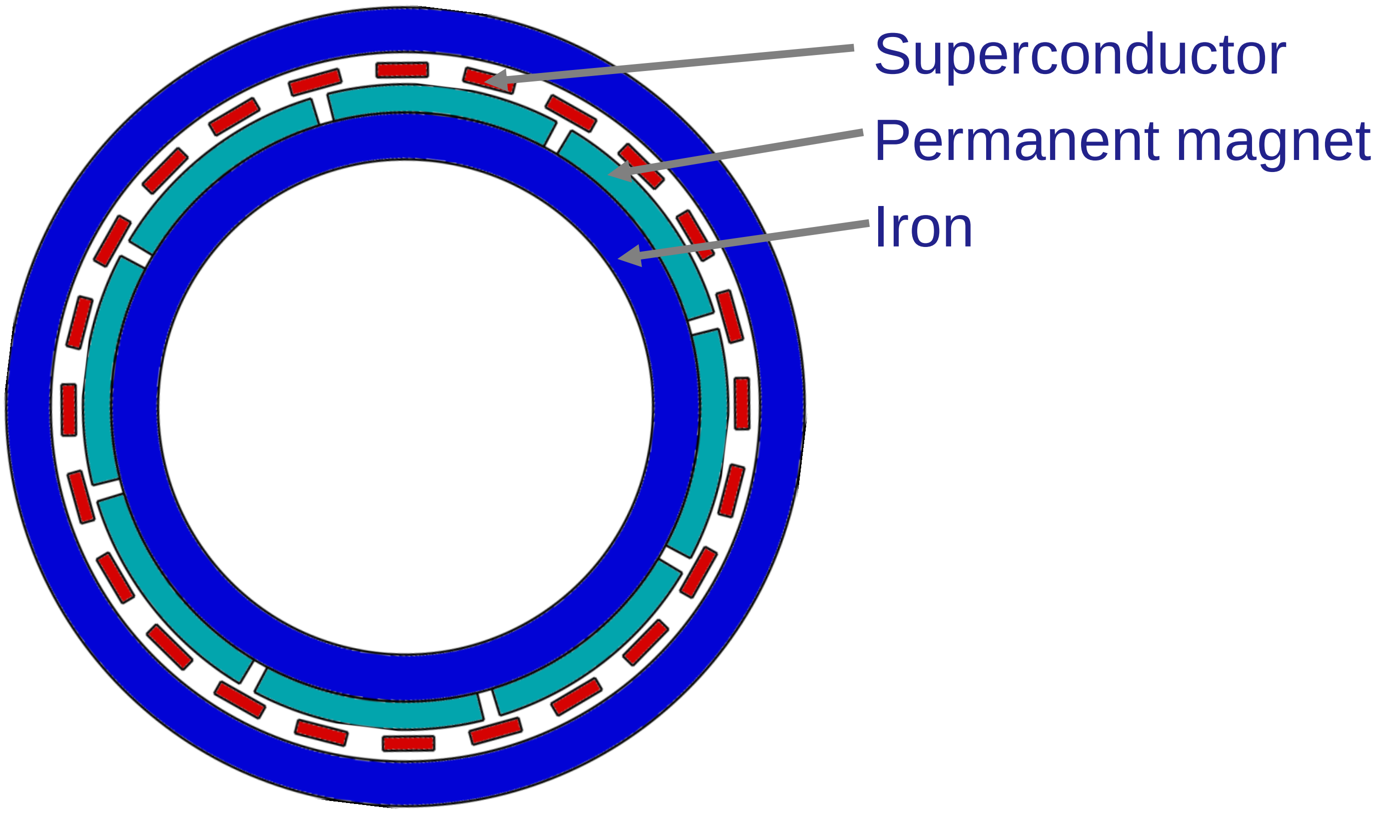
Stator

- Combined method
- Conceptual study
- Final stator results
- Single method for the full motor

Flux pump

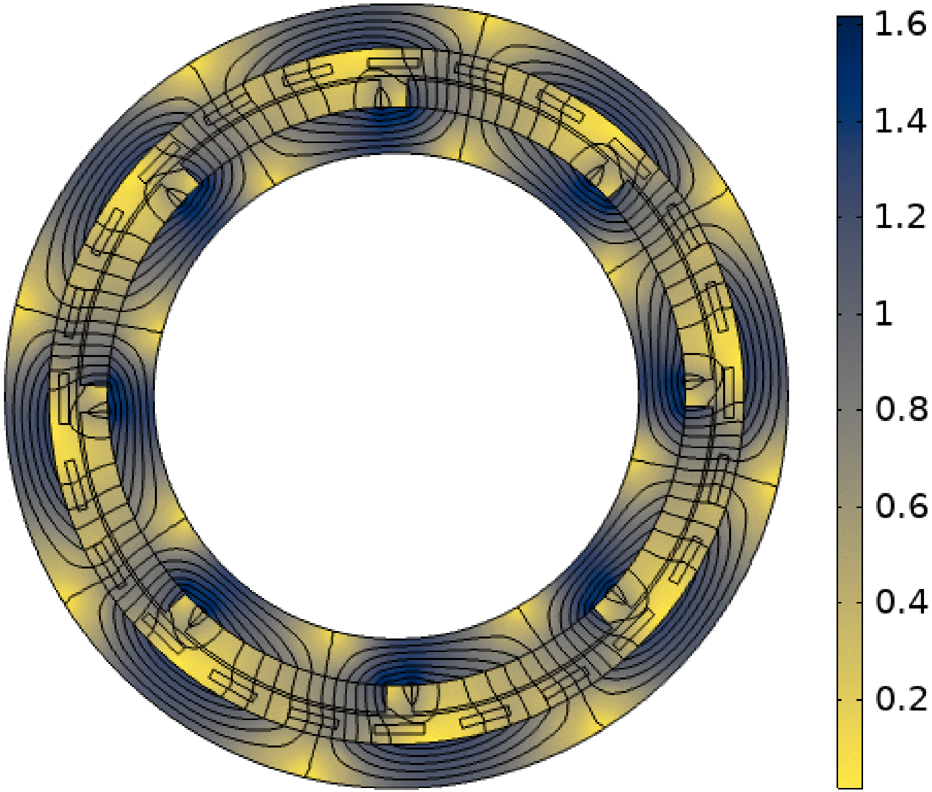
Distributed winding

Funded by the
European Commission
Grant No 723119



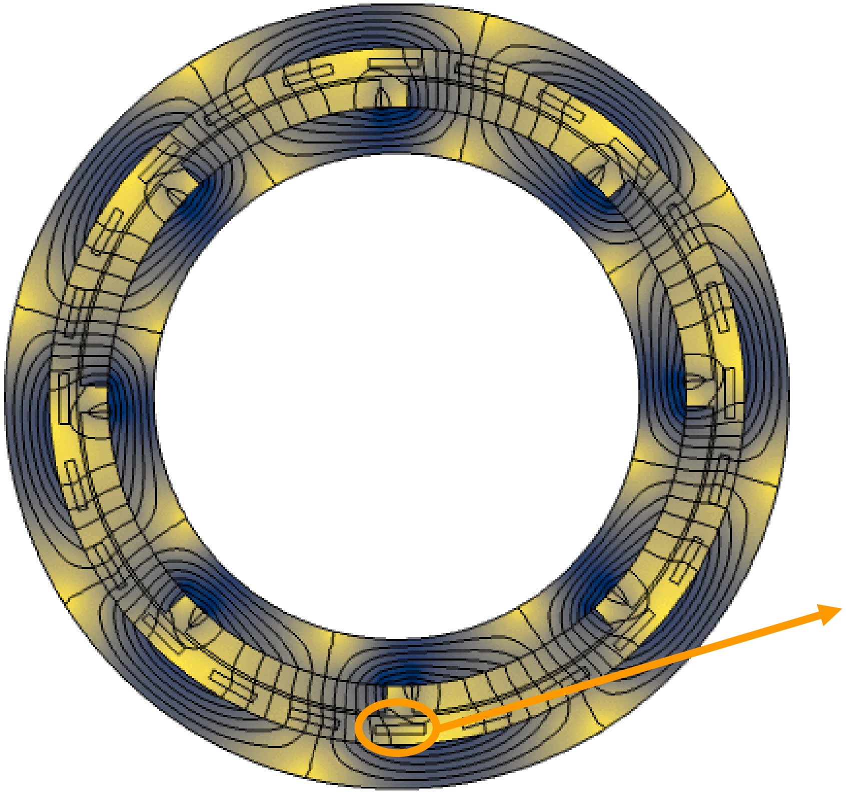
Results for the final stator

Funded by the
European Commission
Grant No 723119



Magnetic flux density [T]

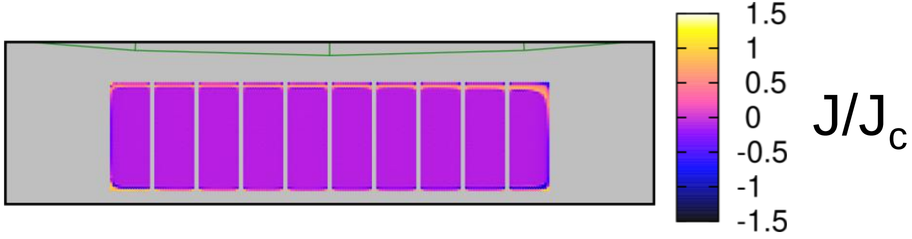
Results for the final stator



3-phase motor

12 coils

Calculations at the peak current

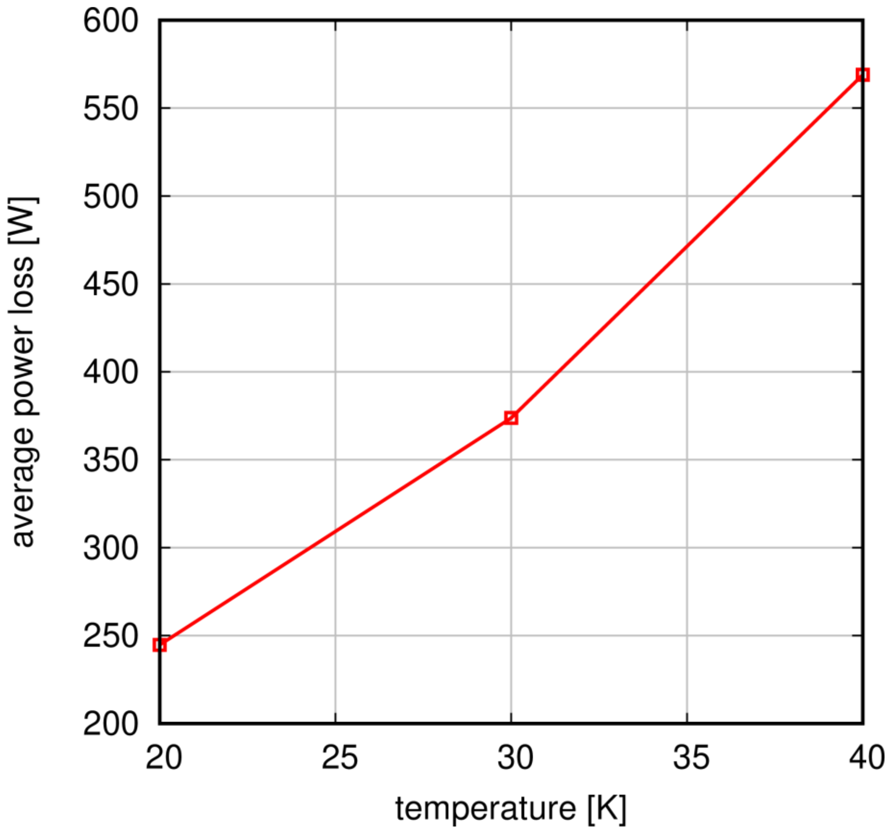


SuperOx tape

Funded by the European Commission Grant No 723119

Very low AC loss!

Funded by the
European Commission
Grant No 723119



Between 0.03 and 0.06 % of total power

Could be optimistic estimation

No J_c reduction at the edges taken into account

Could be pessimistic estimation

New SuperOx material with almost double J_c

Stator

- Combined method
- Conceptual study
- Final stator results
- Single method for the full motor

Flux pump

MEMEP also takes ferromagnetic materials into account

Funded by the European Commission Grant No 723119

We solve

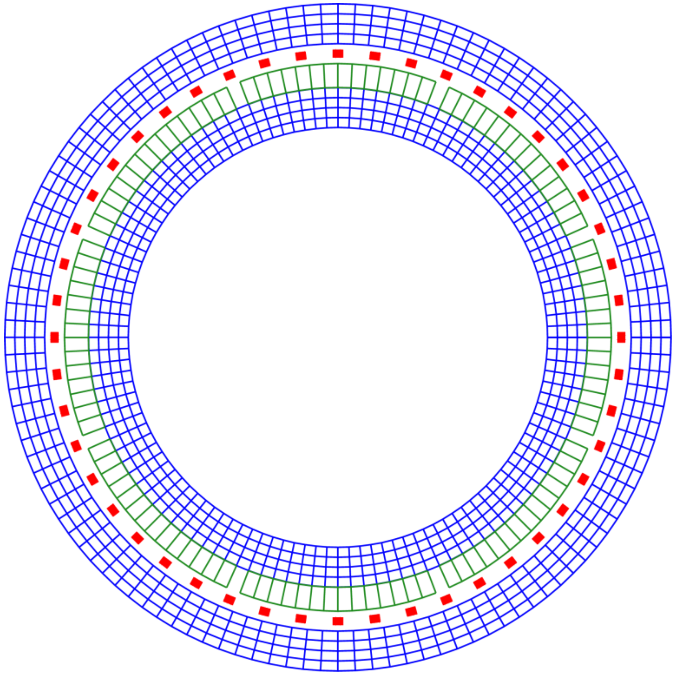
J in the superconductor

M vector in the magnetic material

No need to solve quantities in the air

Easy to make rotation

All interactions taken into account

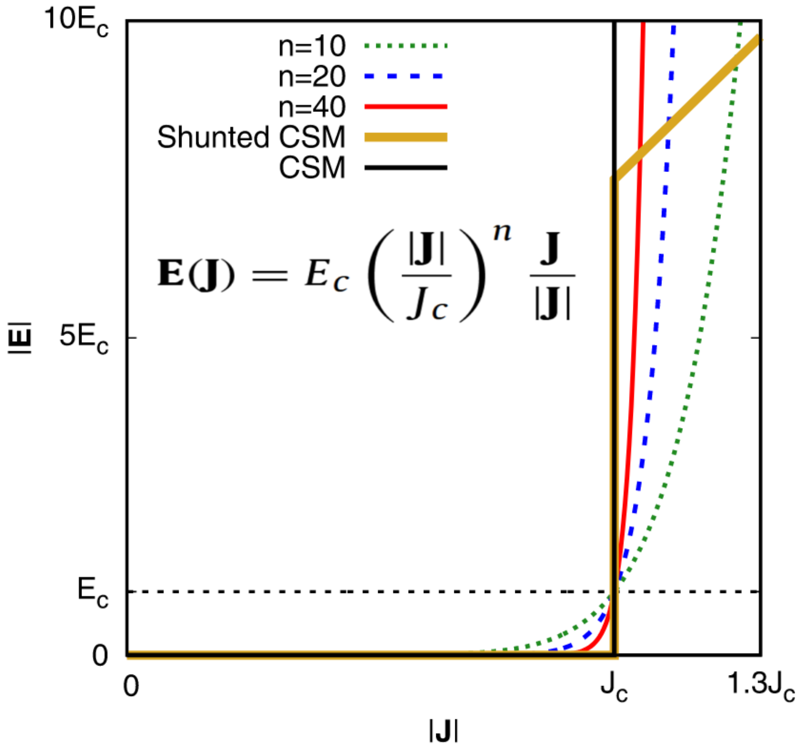


Details in HTS modelling workshop 2018
10.5281/zenodo.1477840

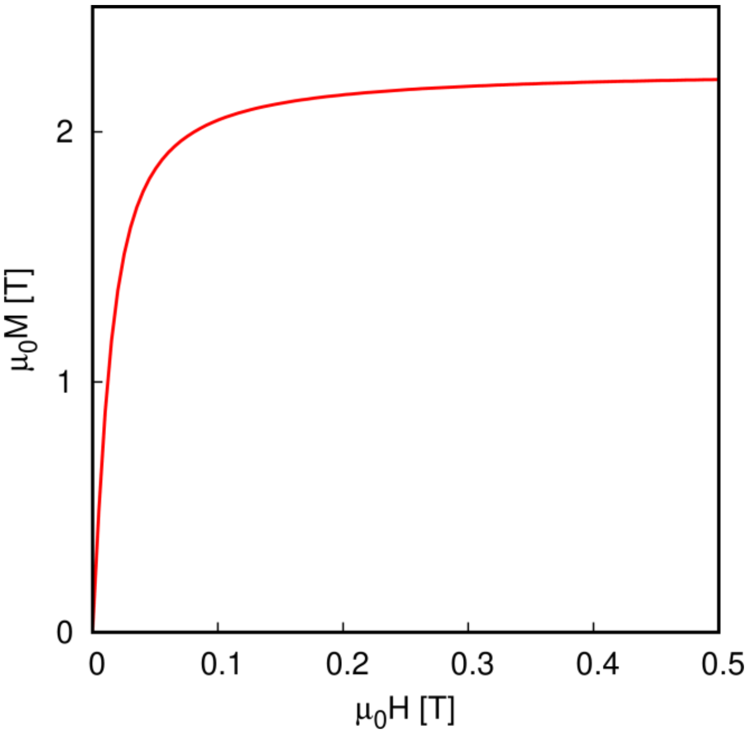
Non-linear materials

Funded by the European Commission Grant No 723119

Superconductor



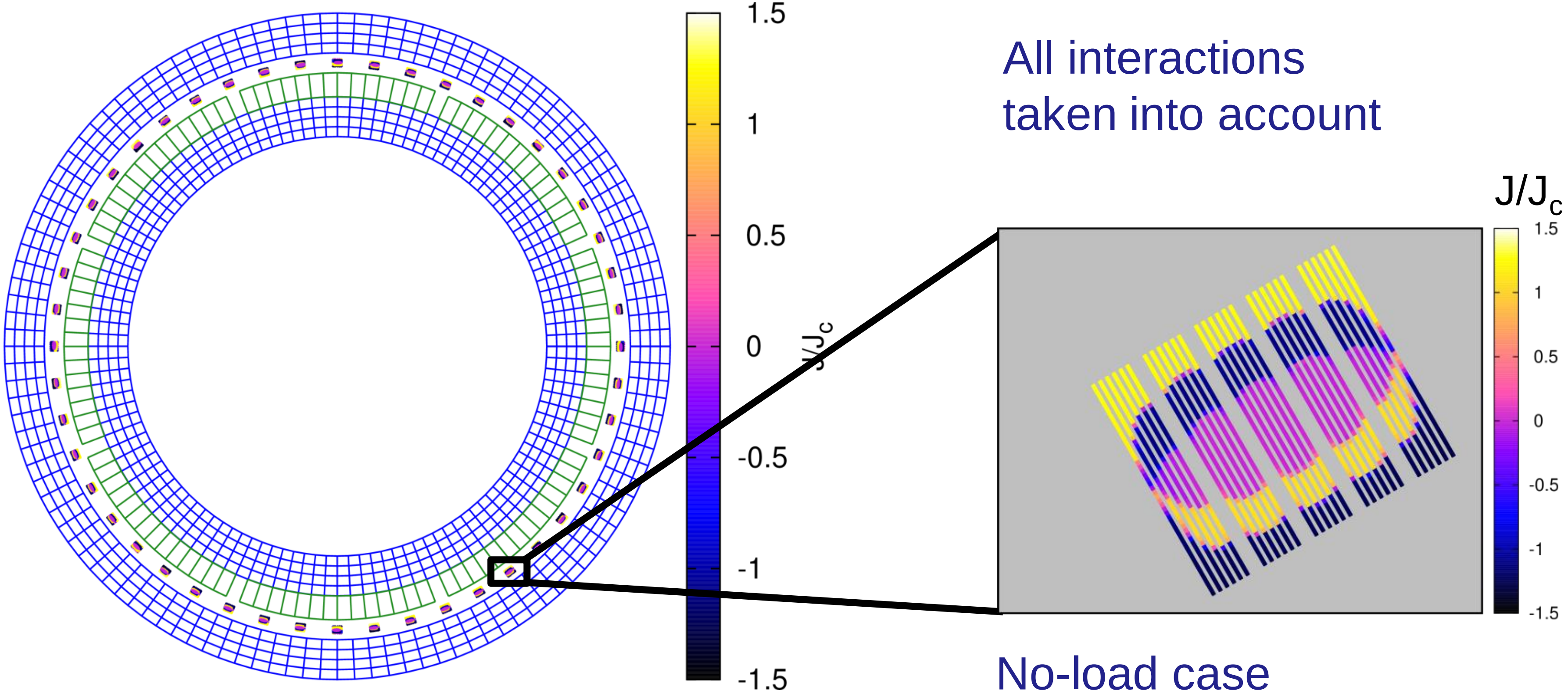
Magnetic material



Non-linear eddy currents in superconductor

Funded by the European Commission Grant No 723119

All interactions taken into account



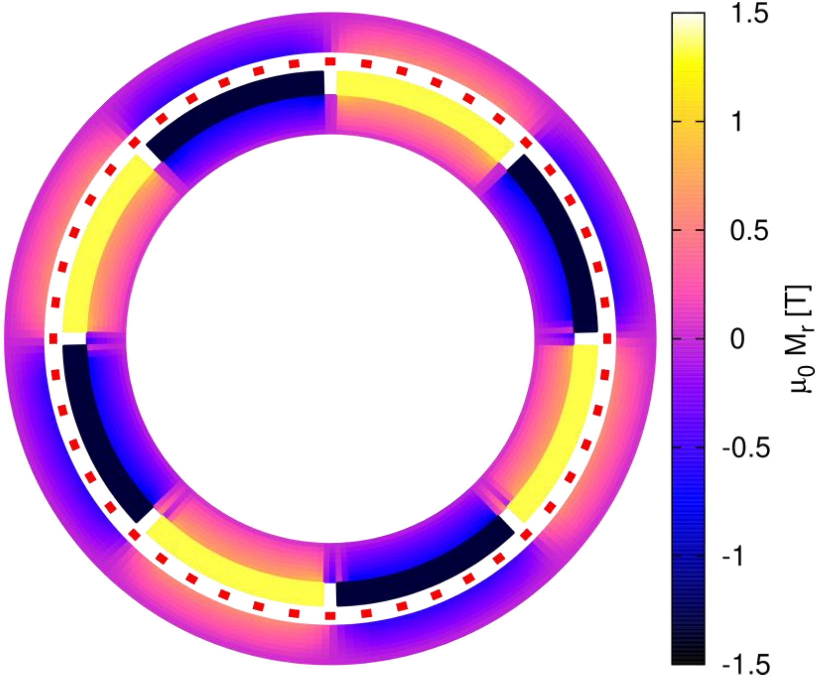
No-load case

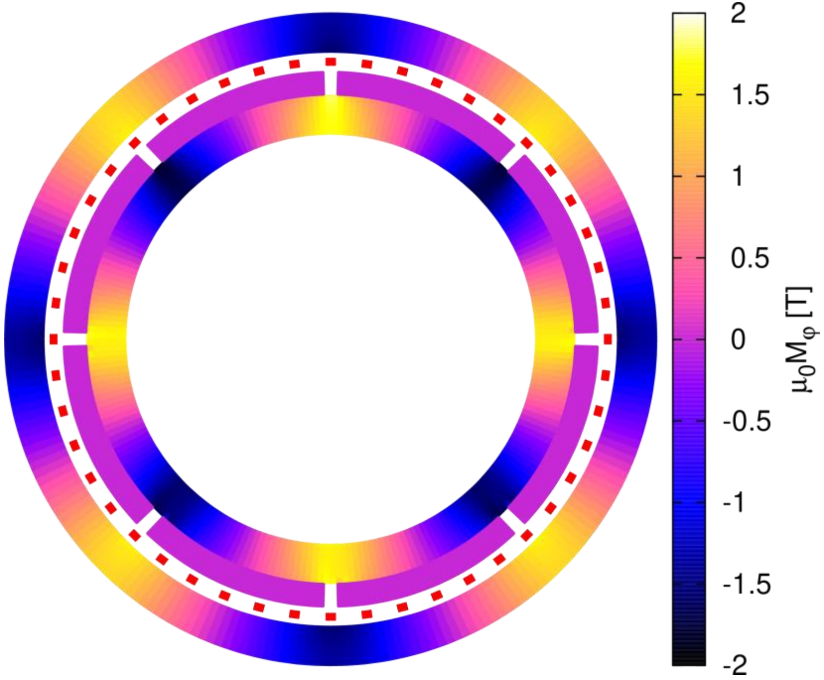
Magnetization in iron and magnets

Funded by the European Commission Grant No 723119

Radial component: m_0M_r [T]

Angular component: m_0M_φ [T]





Stator

Flux pump

Stator

Flux pump

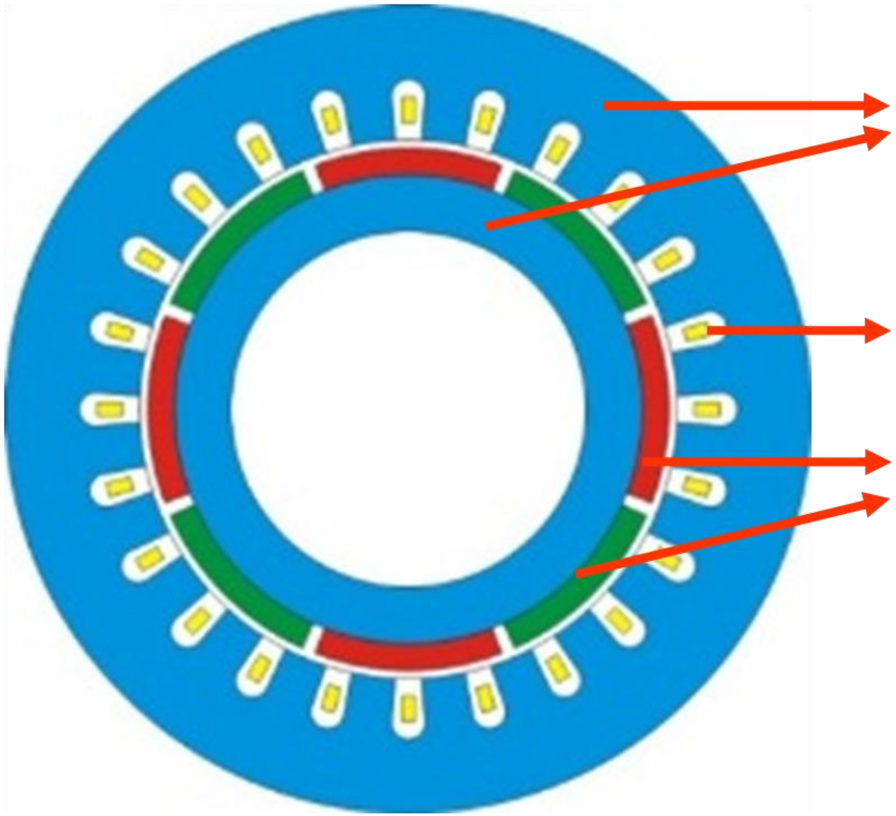
- 3D modelling of screening currents
- Votage signal

Stator

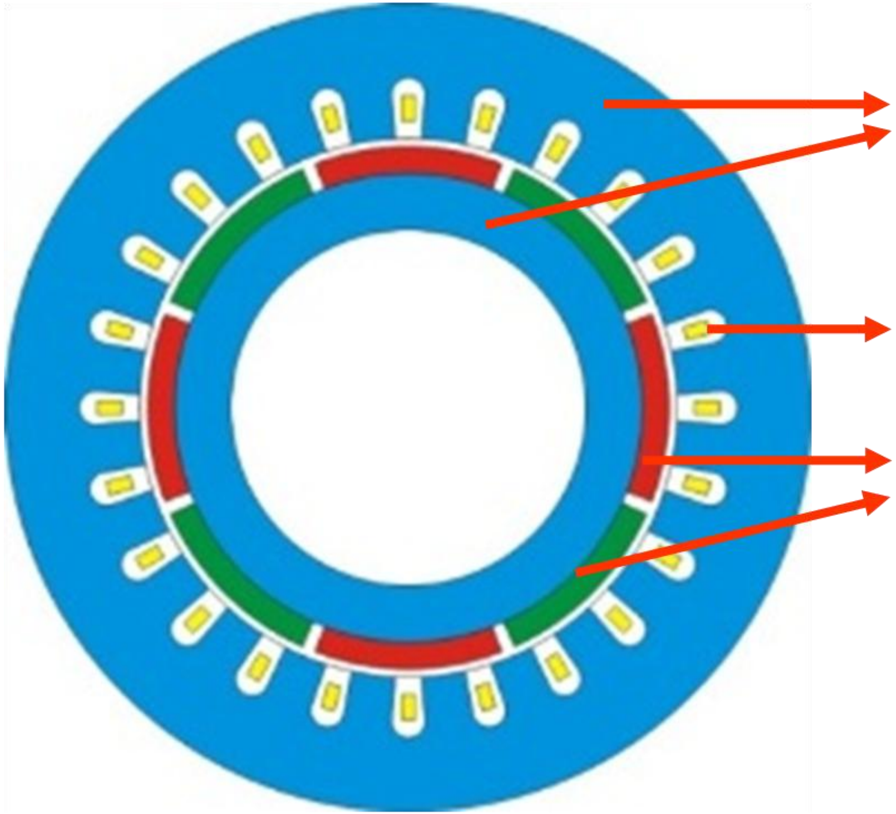
Flux pump

- 3D modelling of screening currents
- Votage signal

Full superconducting motor



Full superconducting motor

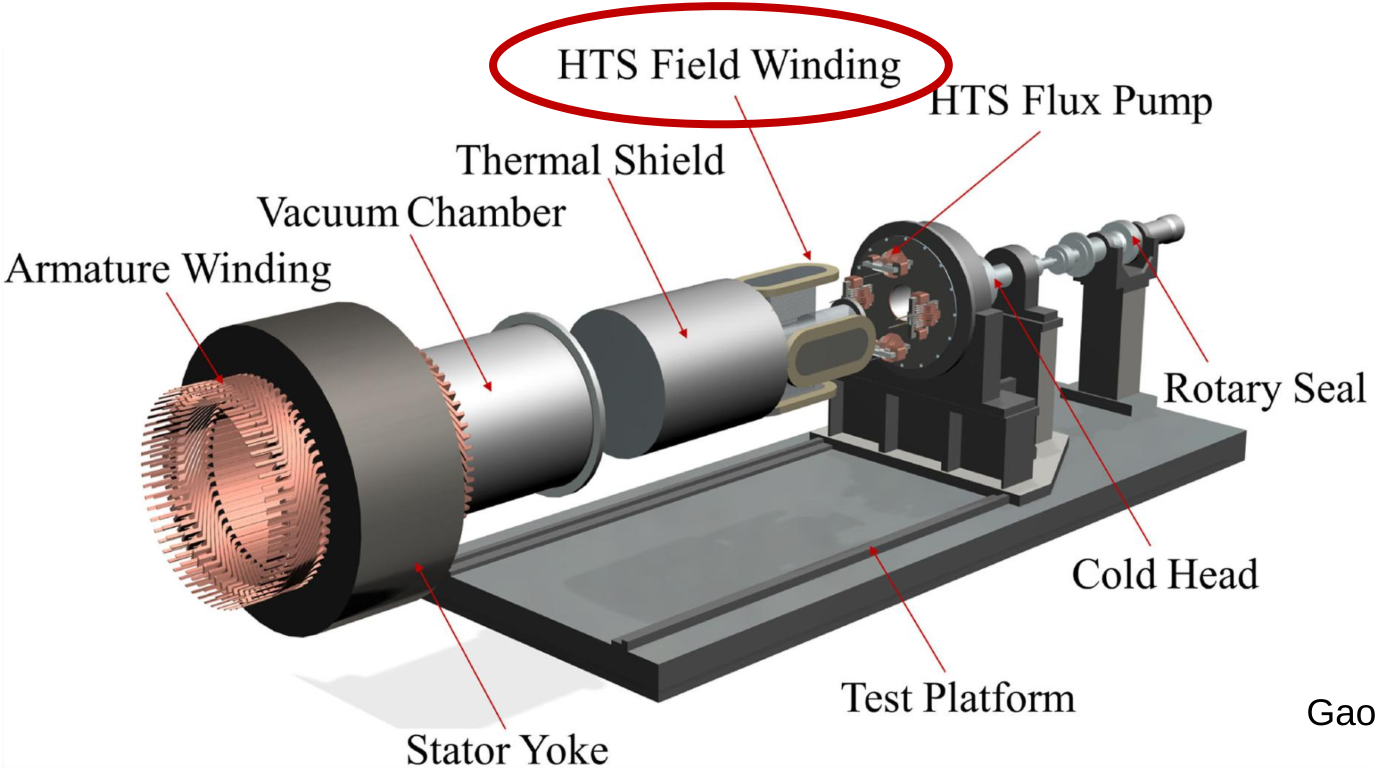


Iron

Superconducting stator

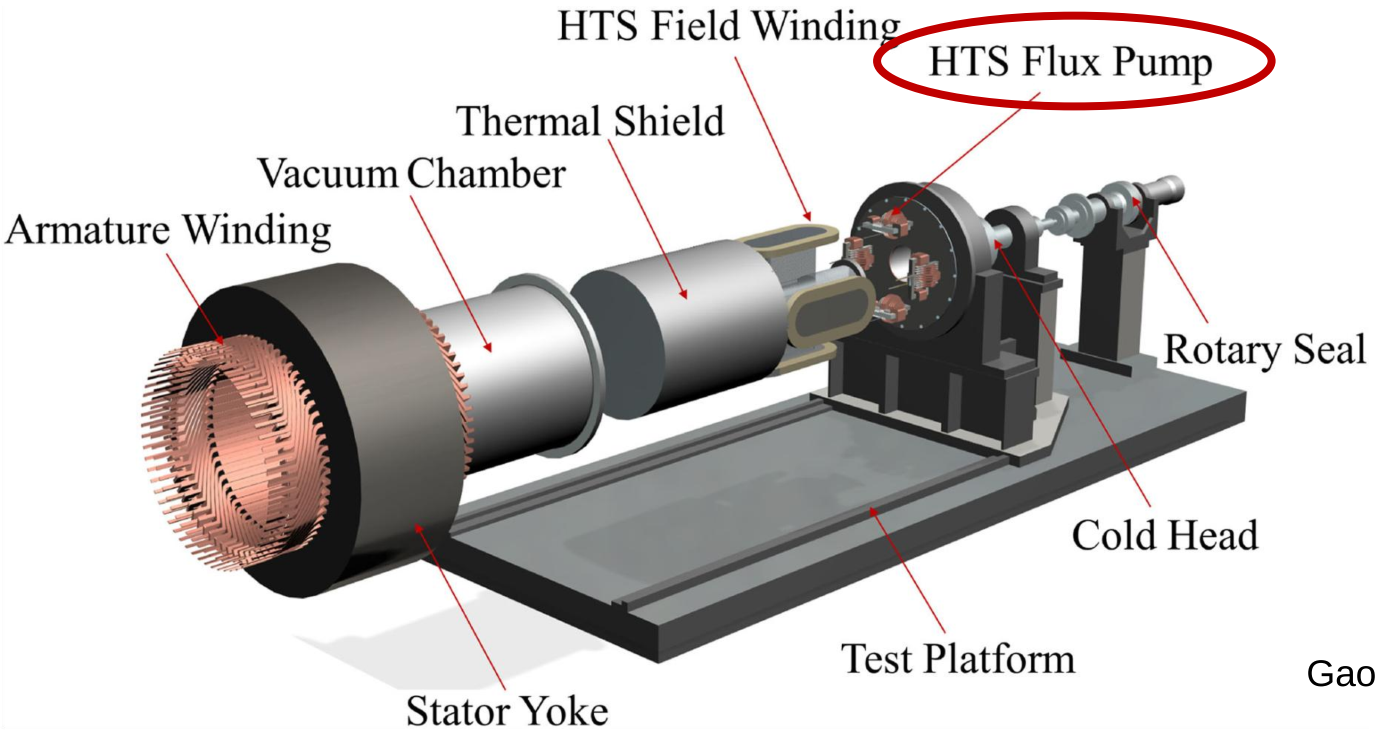
Superconducting magnets **or coils**

Possible to use coils in the rotor



Gao et al. 2019 IEEE TAS

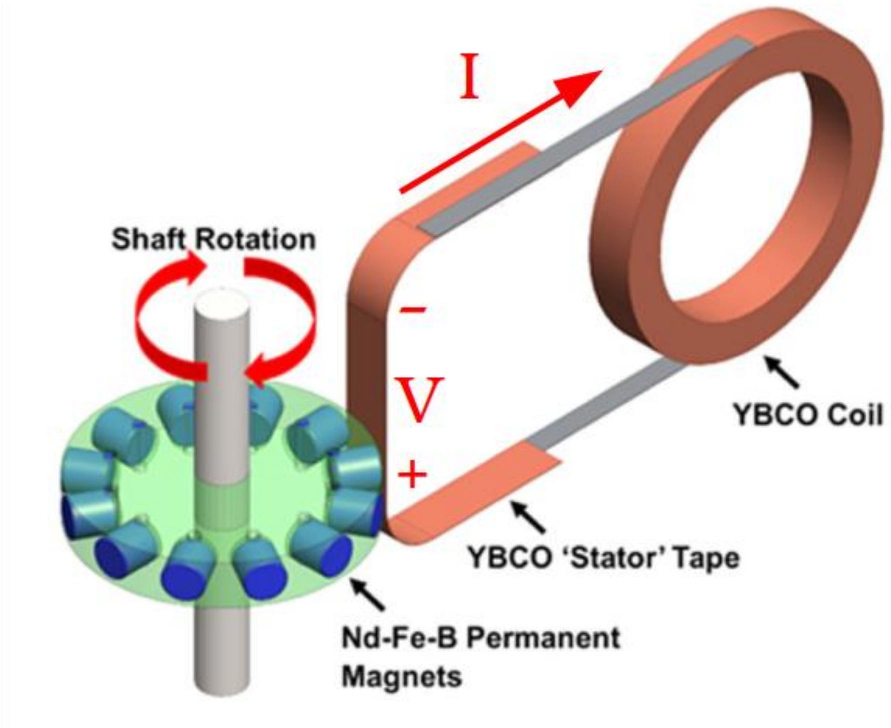
Possible to use coils in the rotor

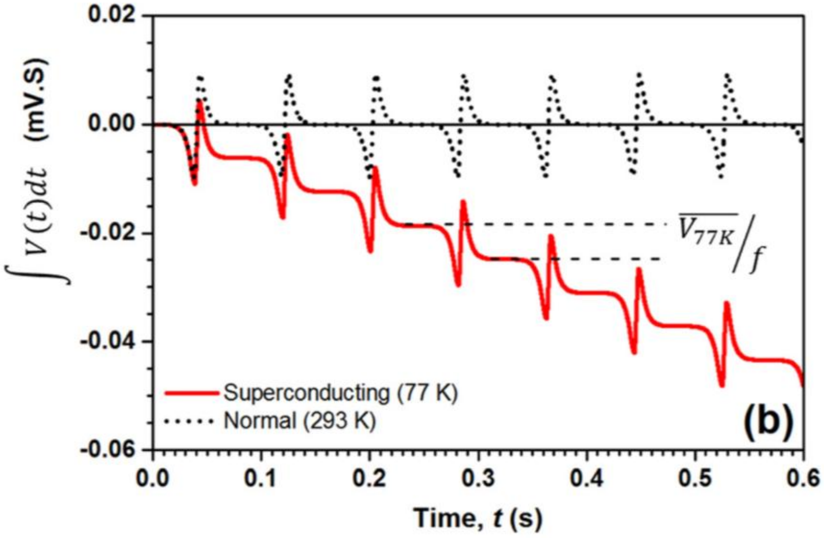


Gao et al. 2019 IEEE TAS

Flux pumps magnetize coils

Confirmed by experiments





Bumby, et al., Appl. Phys. Lett., 2016

Flux pumps can magnetize coils in rotor

Brushless injection of DC current into rotor

Avoids current leads and its thermal load

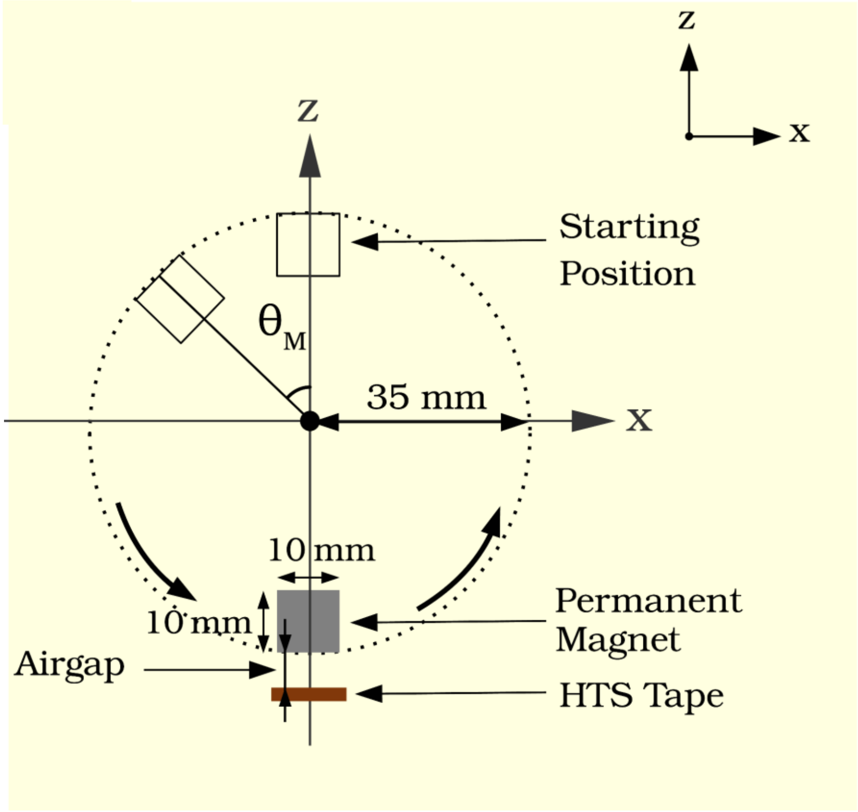
Simplifies cryogenics and maintenance

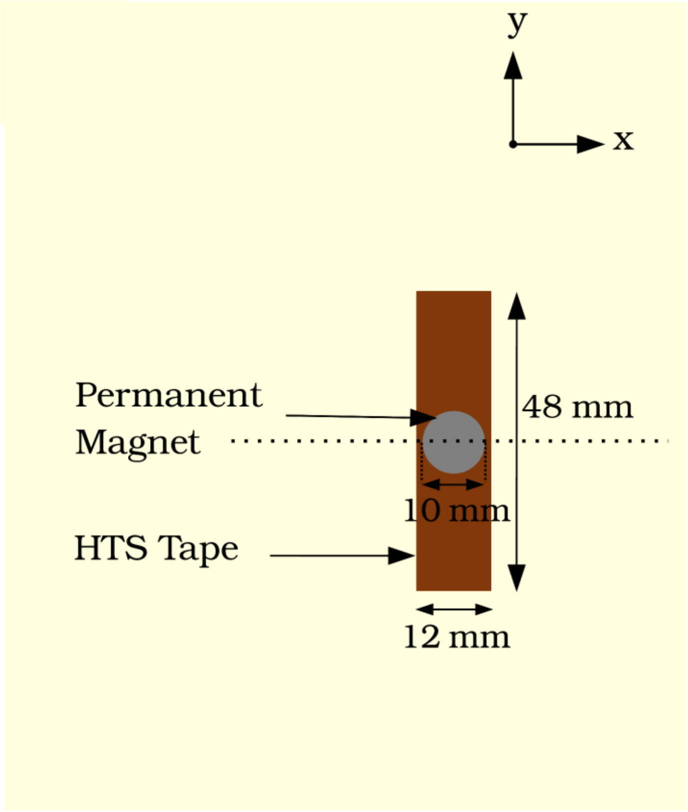
Stator

Flux pump

- 3D modelling of screening currents
- Votage signal

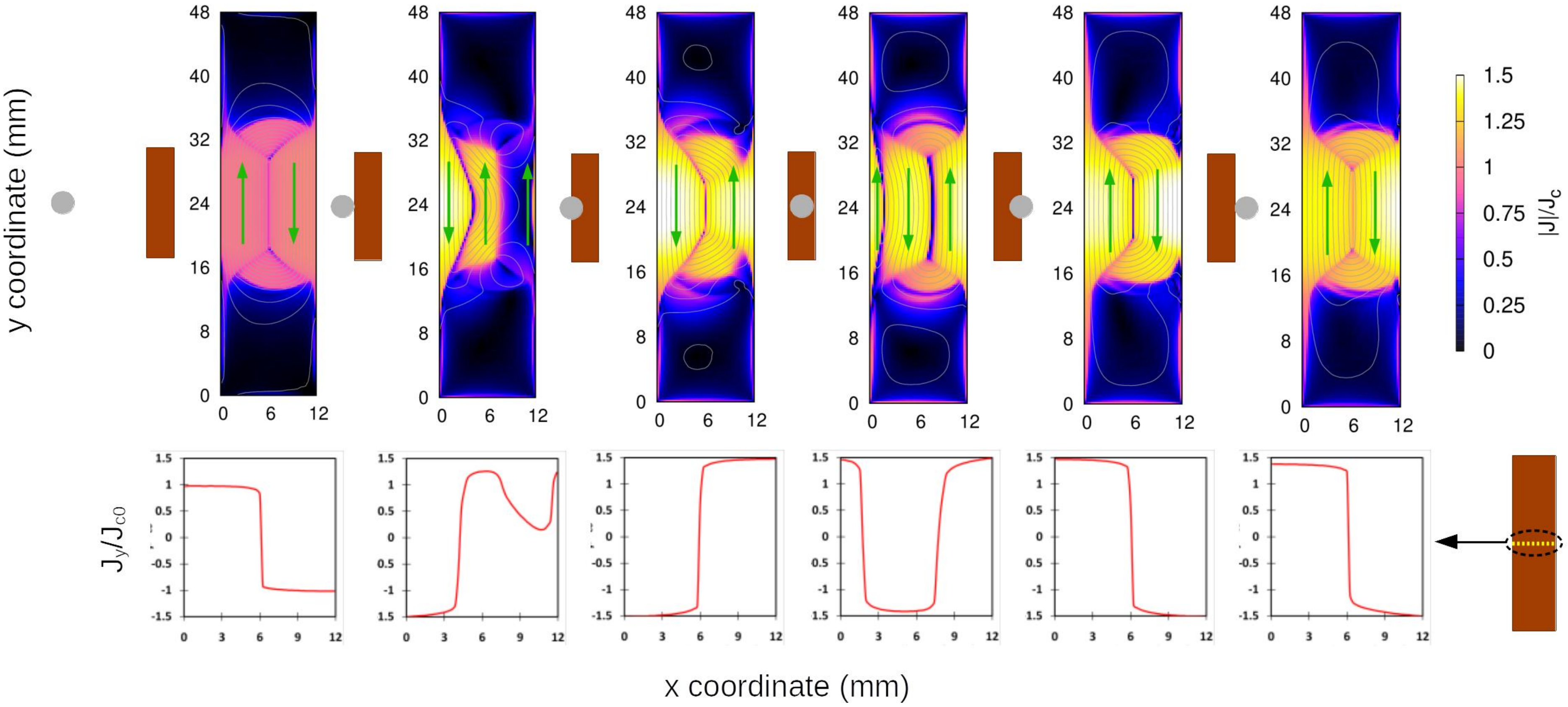
Configuration of 3D model



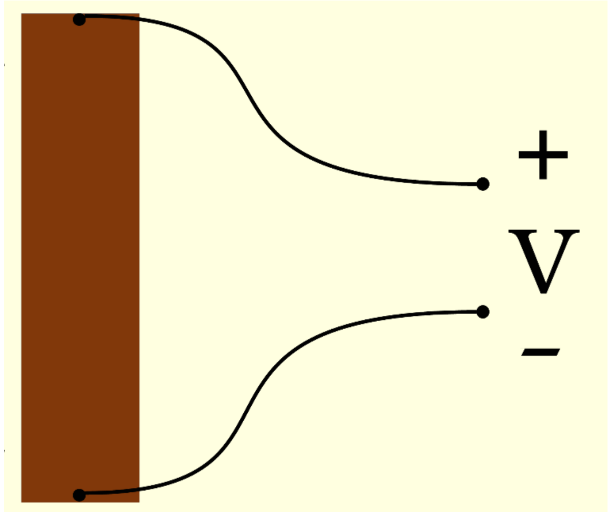


First 3D modelling of flux pump

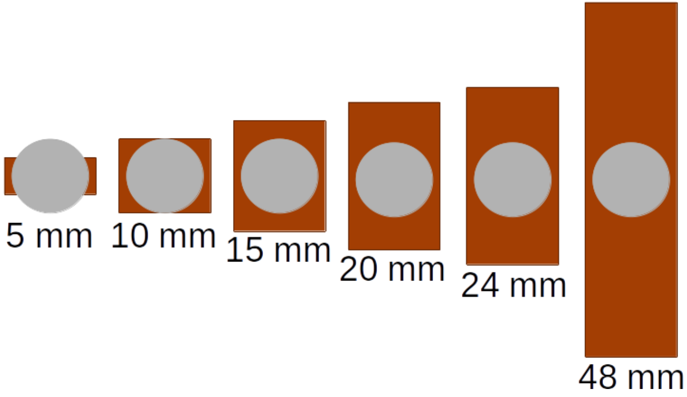
[A Ghabeli, E Pardo, M Kapolka, Scientific Reports 2021]



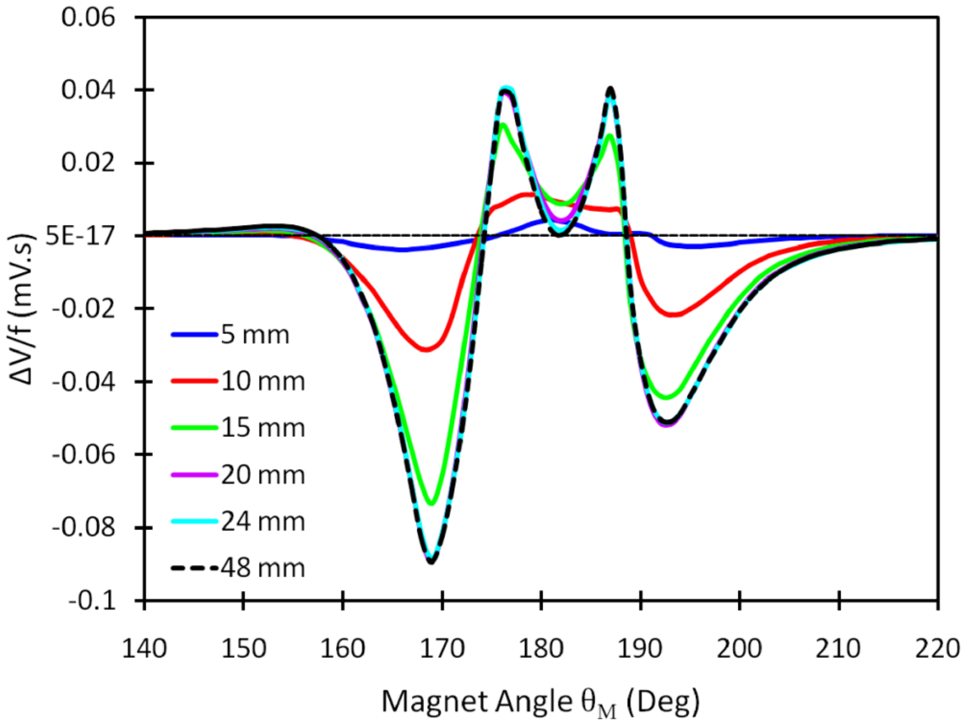
Voltage
and impact of tape length

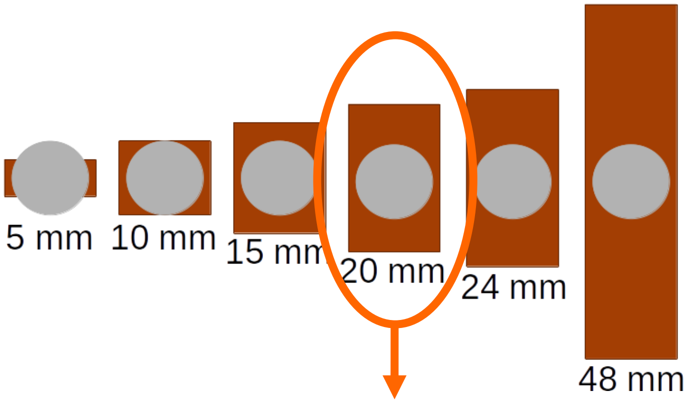


$$\Delta V = V_{77\mathrm{K}} - V_{300\mathrm{K}}$$



Voltage
and impact of tape length





Above 20 mm length voltage remains the same

Conclusion

AC loss of a REBCO stator made of distributied windings

The symmetry of the magnetic flux causes self-transposition

The calculated AC loss is very low for temperatures below 40 K

REBCO stators are feasible!

First 3D modelling of flux pump

Visualization of 3D screening currents

Minimum voltage taps distance depends on:

Magnet diameter

Distance between magnet and tape surface

See you soon!

Thank you for your attention!

Would you like to know more?

enric.pardo@savba.sk

Variational principle for the magnetic material

Equation

$$\mathbf{B}(\mathbf{M}) = \mathbf{B}_M + \mathbf{B}_a + \mathbf{B}_J$$

- $\mathbf{B}(\mathbf{M})$: non-linear relation
- $\mathbf{B}_M$: **B** created by $\nabla\times$**M**
- $\mathbf{B}_a$: applied **B**
- $\mathbf{B}_J$: **B** from currents

is the Euler equation of

$$L_M = \int_V \mathrm{d}V \left[U(\mathbf{M}) - \frac{1}{2}\mathbf{B}_M \cdot \mathbf{M} - \mathbf{B}_a \cdot \mathbf{M} - \mathbf{B}_J \cdot \mathbf{M} \right]$$

$$U(\mathbf{M}) = \int_0^{\mathbf{M}} \mathrm{d}\mathbf{M}' \cdot \mathbf{B}(\mathbf{M}')$$

Variational principle for the magnetic material

$$L_M = \int_V \mathrm{d}V \left[U(\mathbf{M}) - \frac{1}{2}\mathbf{B}_M \cdot \mathbf{M} - \mathbf{B}_a \cdot \mathbf{M} - \mathbf{B}_J \cdot \mathbf{M} \right]$$

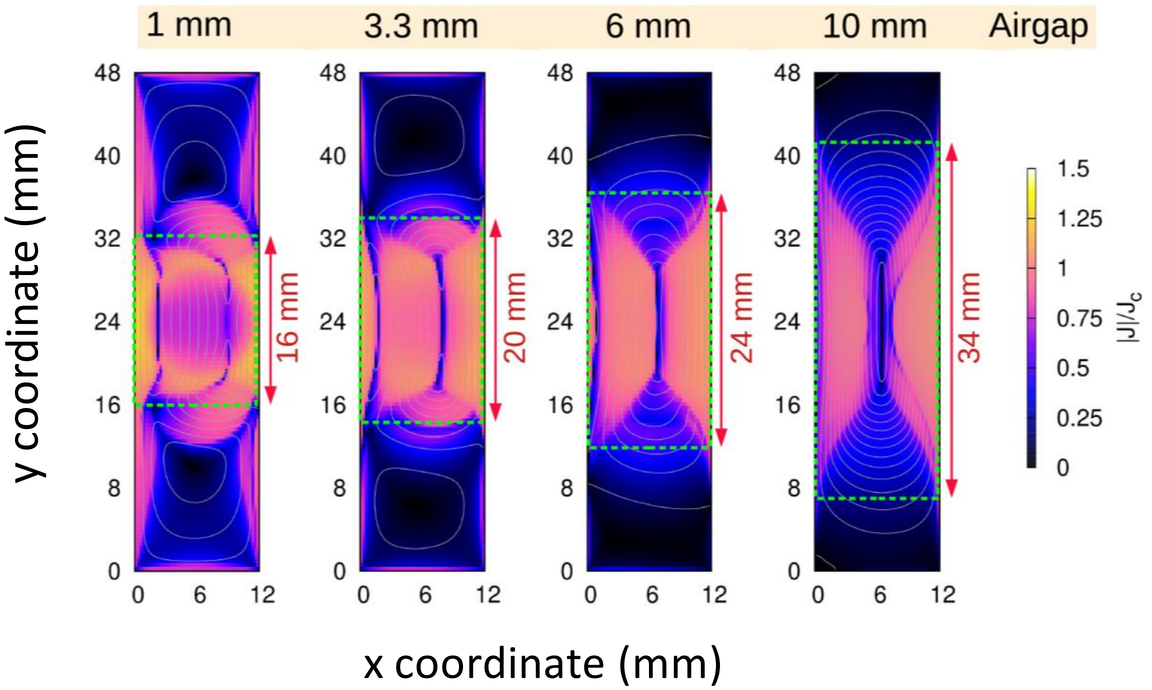
$$U(\mathbf{M}) = \int_0^{\mathbf{M}} \mathrm{d}\mathbf{M}' \cdot \mathbf{B}(\mathbf{M}')$$

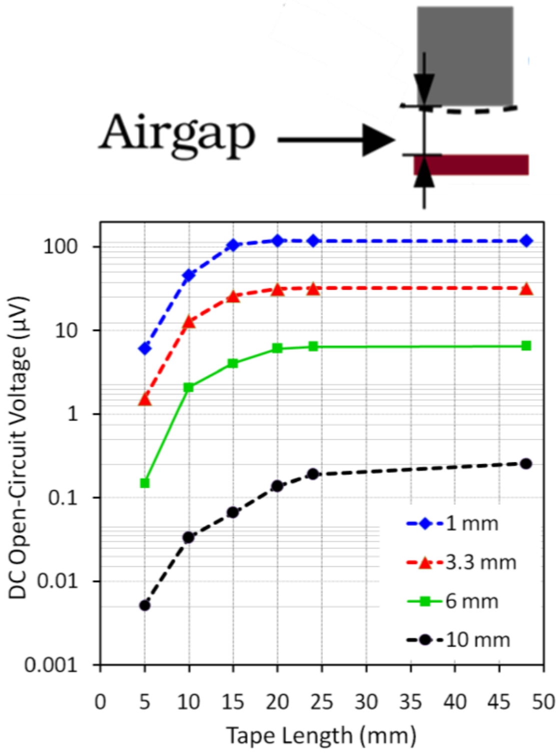
Problem restricted to the magnetic material volume

Functionals for magnetic material and superconductor **solved iteratively**

Impact of Airgap on Voltage Taps distance

$J_c(B,\theta)$
f = 12.3 Hz





Voltage taps distance depends also on airgap value other than diameter of magnet