# AC loss in the distributed stator winding of a 1 MW motor for aviation

**E Pardo,** S Li

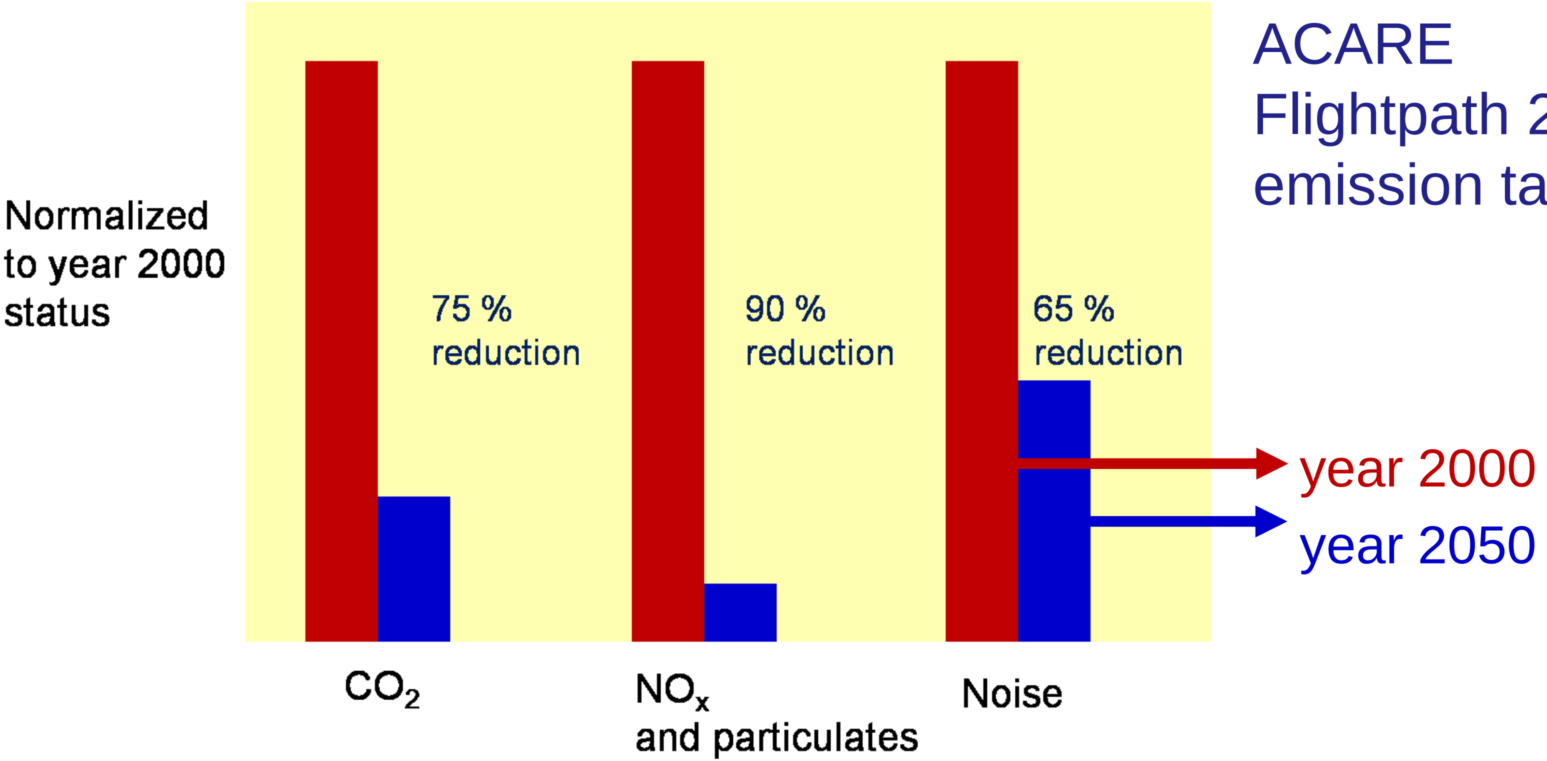
F Grilli, Y Liu, T Benkel

S Wolfstaedler, E Berberich, T Reis

Karlsruhe Institute of Technology

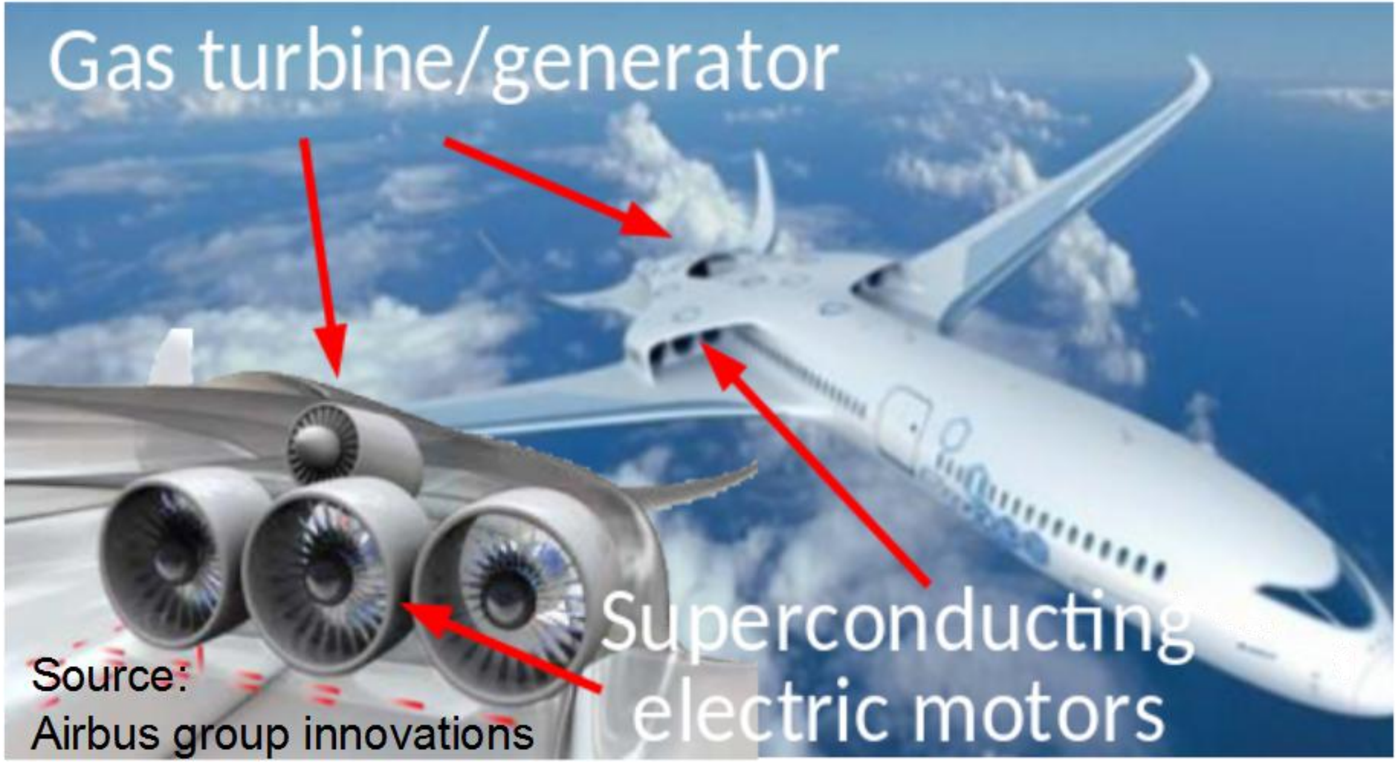
# The European Union wants to reduce emissions

## Drastic reductions need drastic improvements

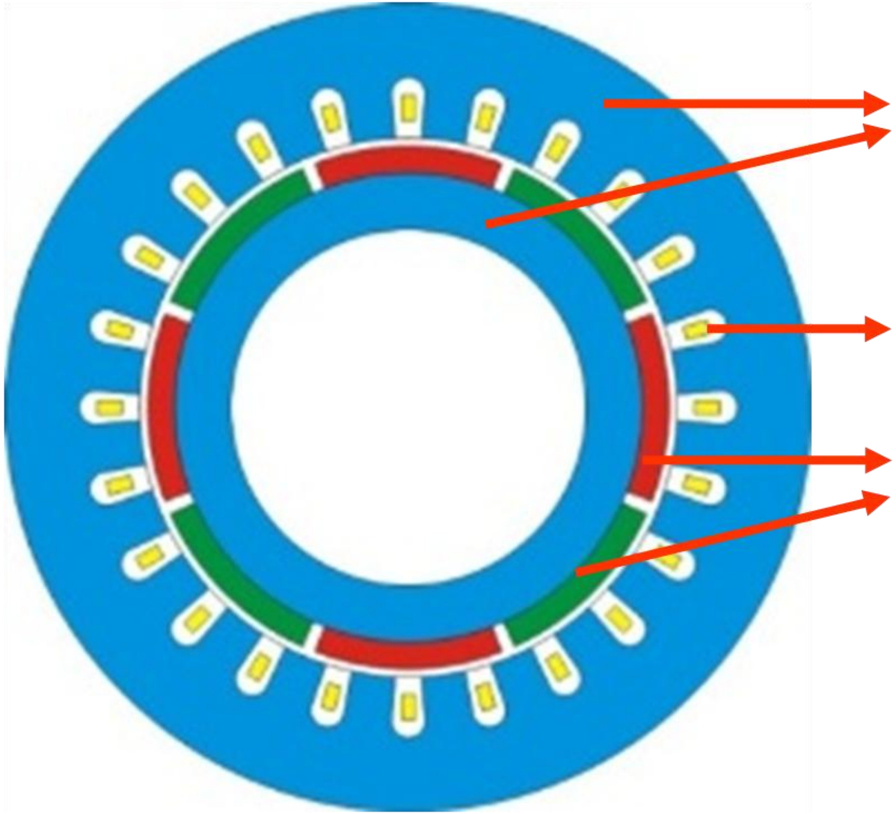



ACARE
Flightpath 2050
emission targets

# Reduction possible
# by hybrid distributed propulsion



# Superconducting motor

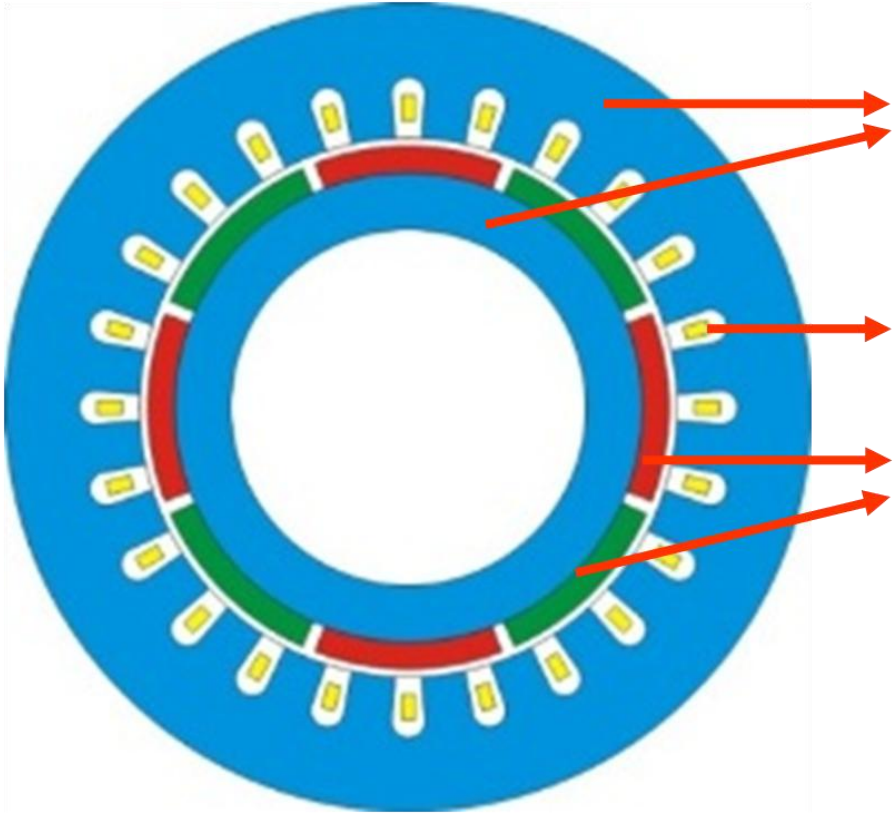


Iron

**Superconducting stator**

Permanent magnets

# Full superconducting motor



Iron

**Superconducting stator**

**Superconducting magnets or coils**

# AC loss in the distributed stator winding of a 1 MW motor for aviation

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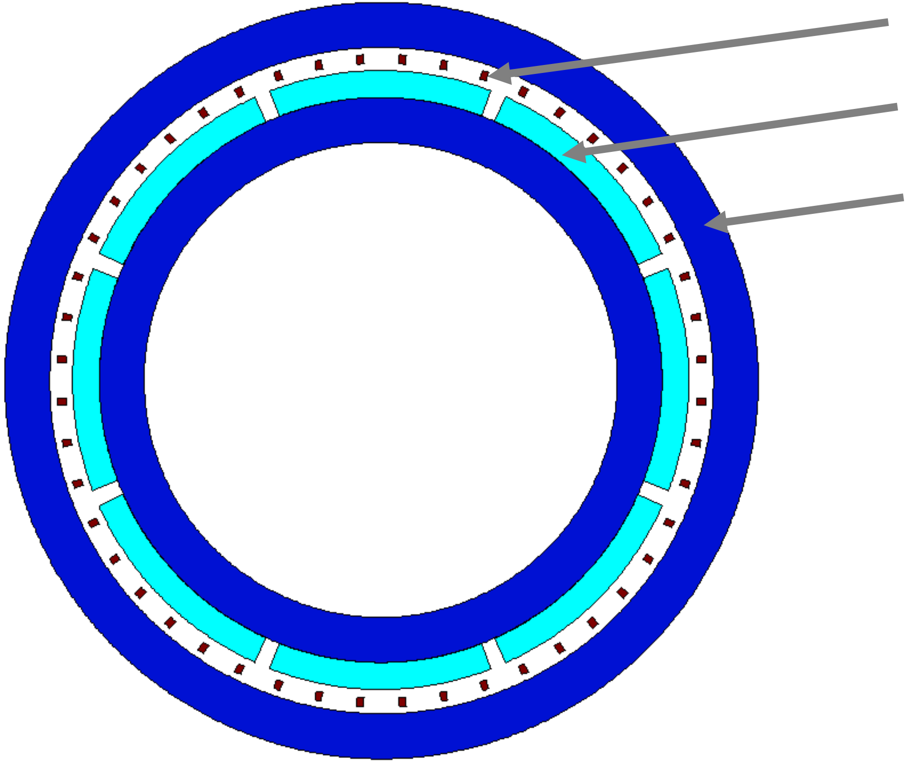
# Advanced Superconductor Motor Demonstrator (ASuMED)

Horizon 2020 project
funded by
the European Commission

# Distributed winding

Funded by the European Commission Grant No 723119




**Lower harmonics in the rotor**

**Higher specific power than concentrated windings**

Design from Oswald

**Combined numerical method**

**AC loss results**

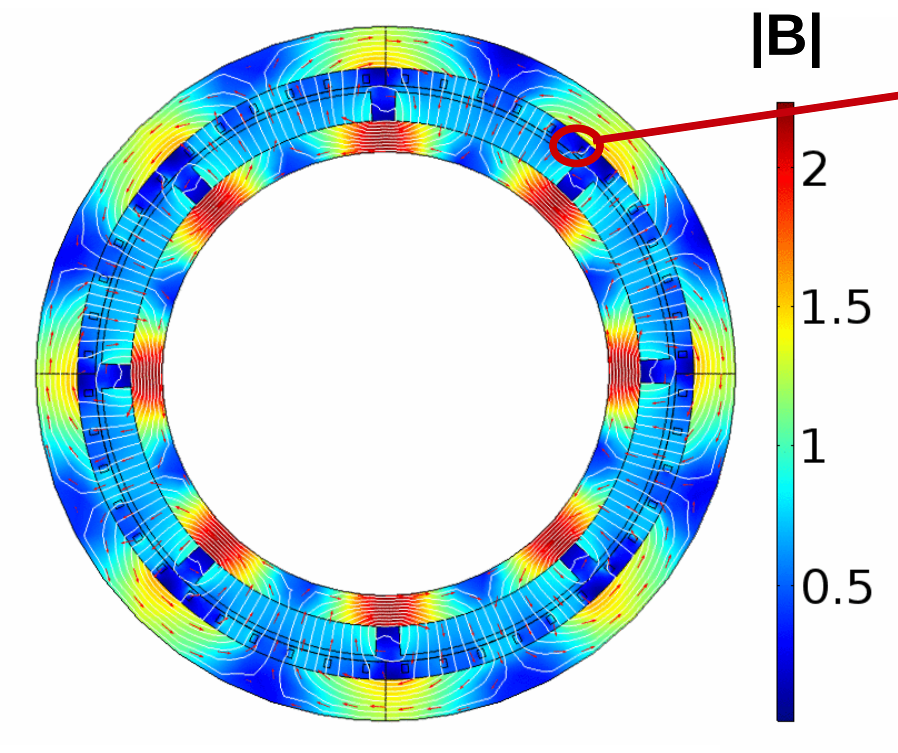
**Novel modelling approach**

**Combined numerical method**

**AC loss results**

**Novel modelling approach**

# 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

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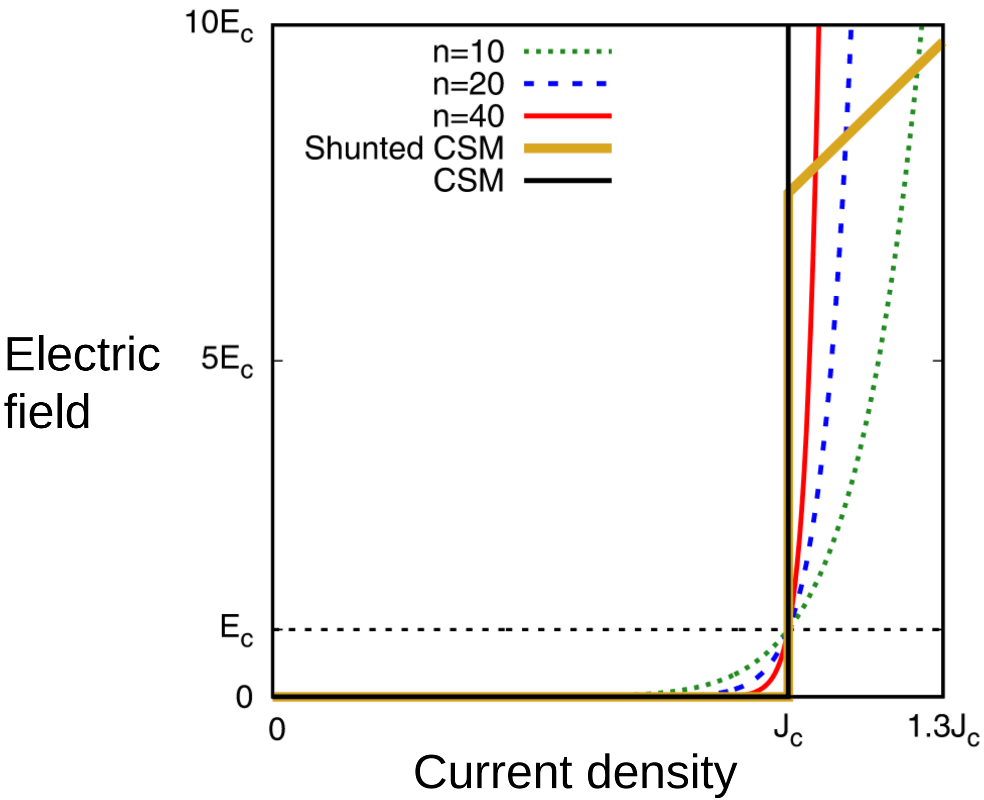



Flux-creep relation

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

# 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

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

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

→

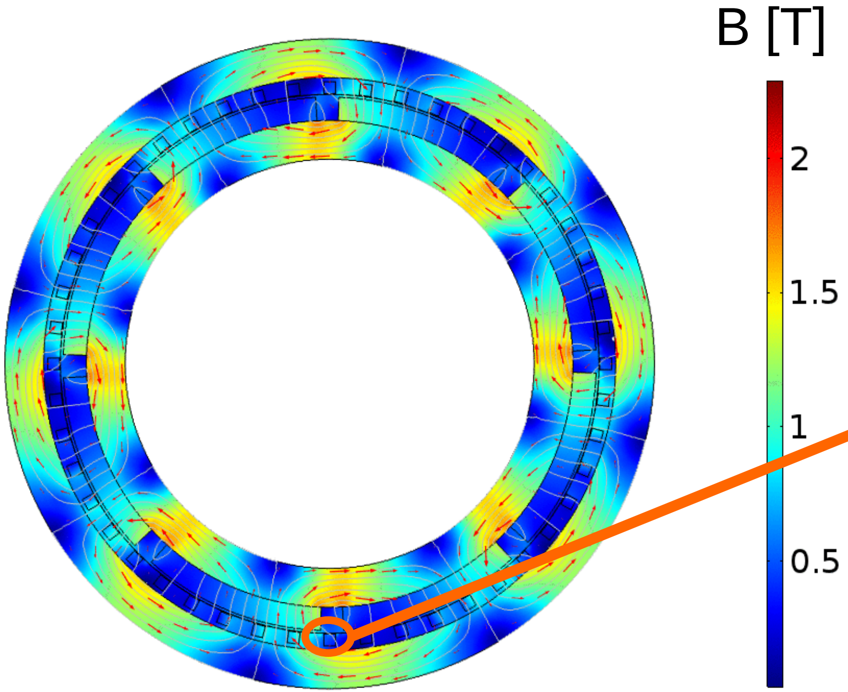
MEMEP calculates non-uniform **J** and AC loss

**Fast method**

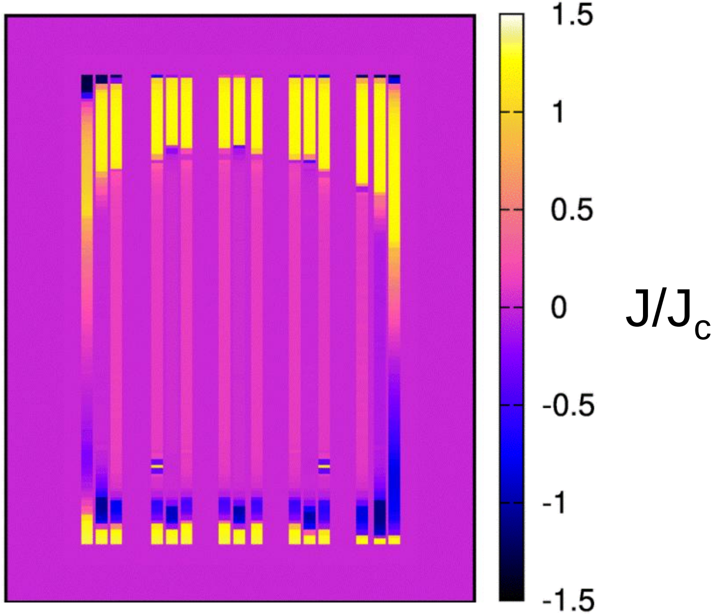
**Ideal to optimize the superconductor windings**

# MEMEP calculates non-linear eddy currents and AC loss

Funded by the European Commission Grant No 723119

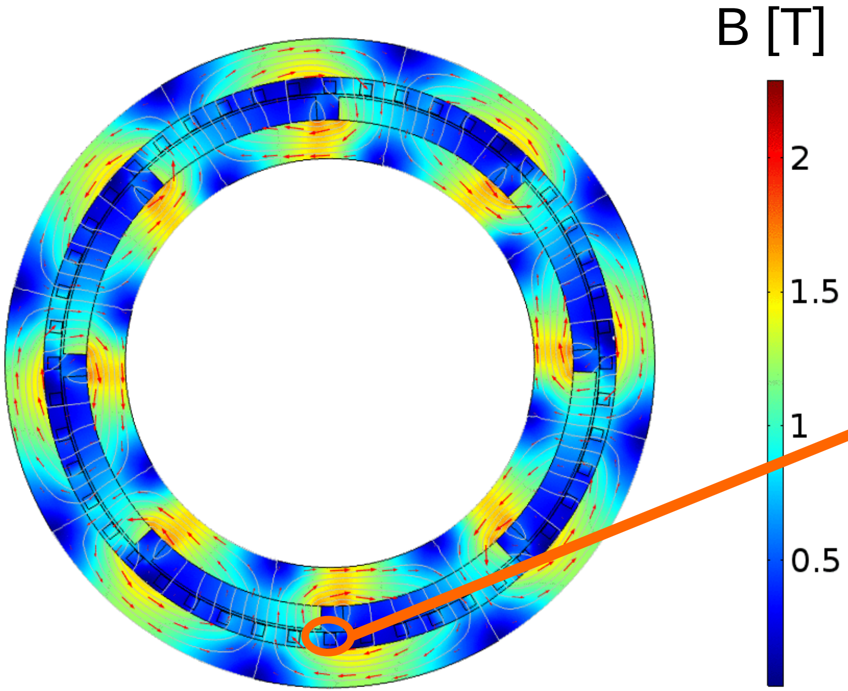



**more than 1000 tapes**

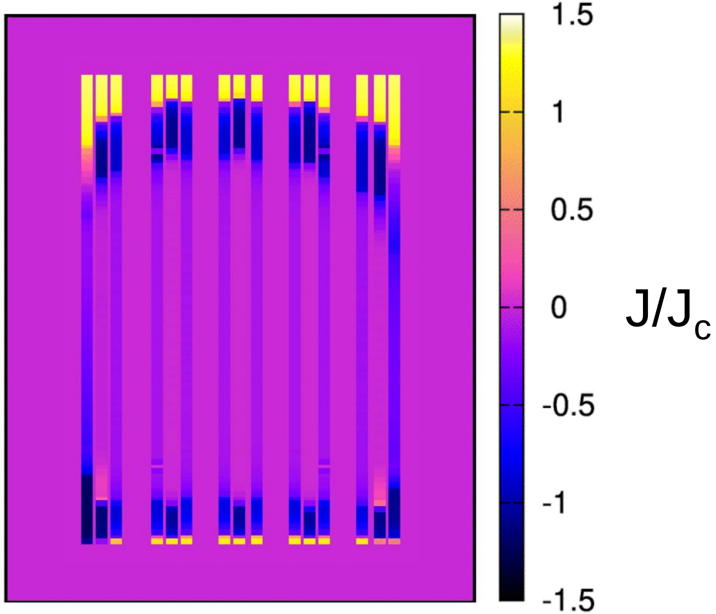


# MEMEP calculates non-linear eddy currents and AC loss

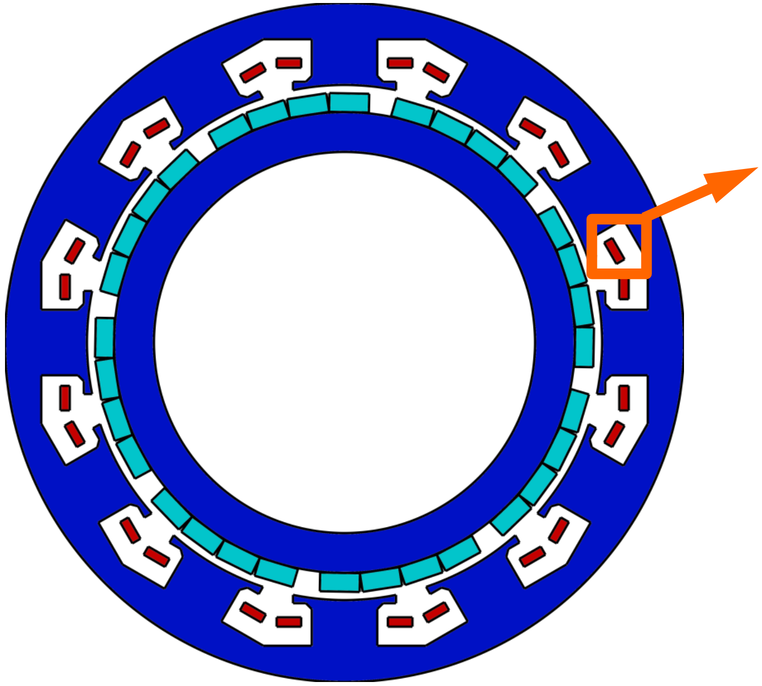
ASuMED
Funded by the European Commission Grant No 723119

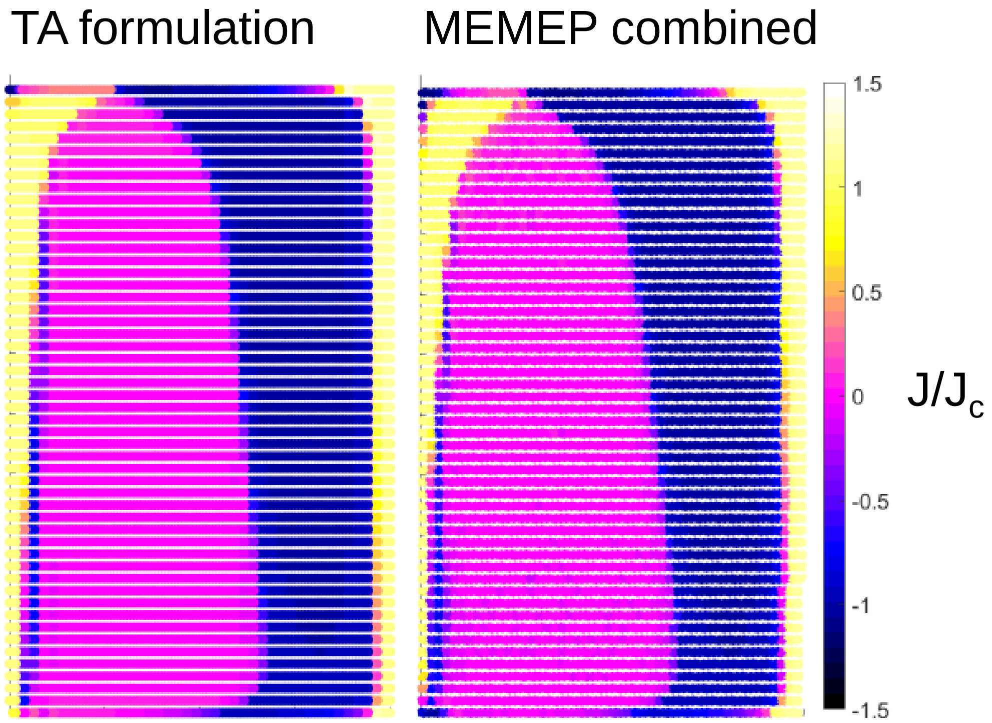



## more than 1000 tapes



# Combined model agrees with FEM in TA formulation






T Benkel et al., Wednesday presentation

Combined numerical method

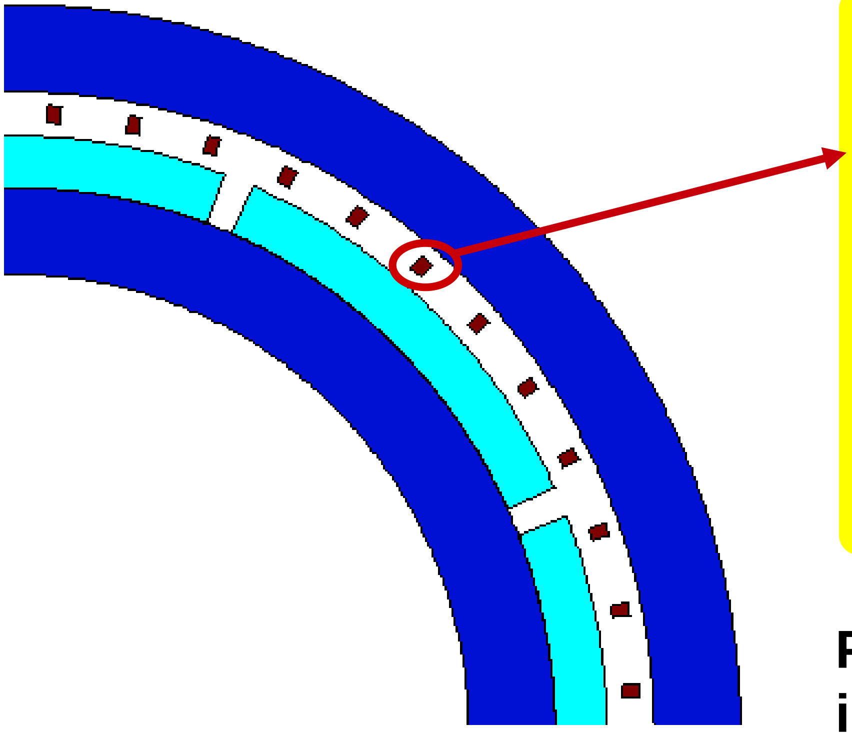
AC loss results

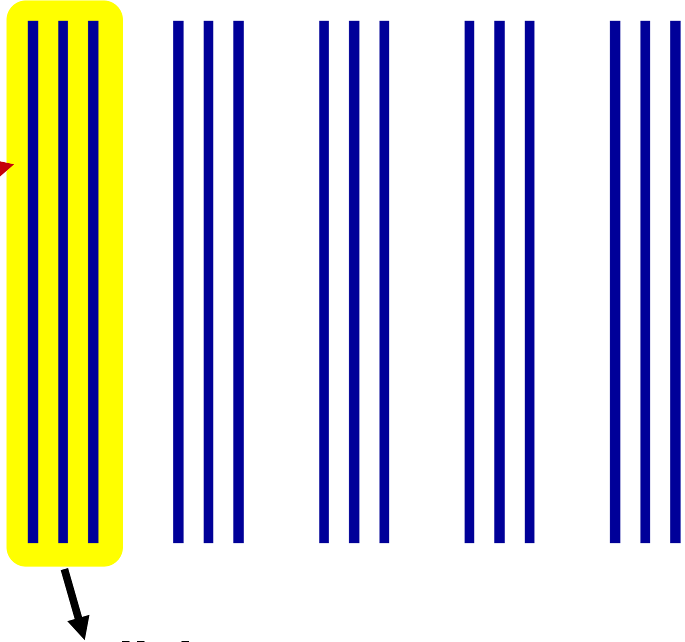
Effect of coupling

Temperature and field dependence

**Novel modelling approach**

# Base cross-section: 3-tape conductor





Parallel tapes in conductor



Funded by the European Commission Grant No 723119

# Coupling configurations

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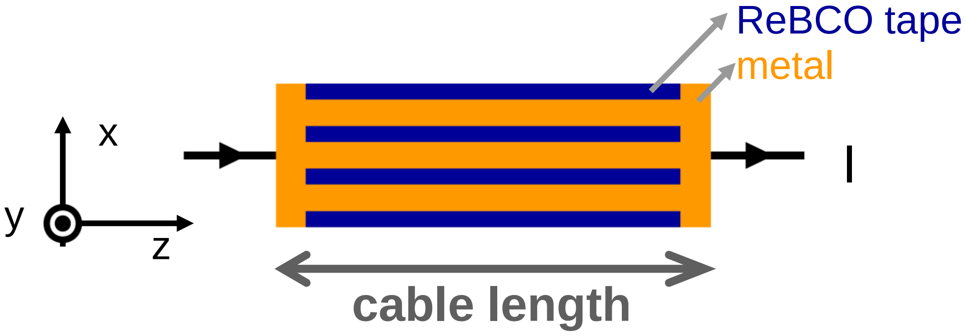
Coupled




Coupled at ends


Uncoupled

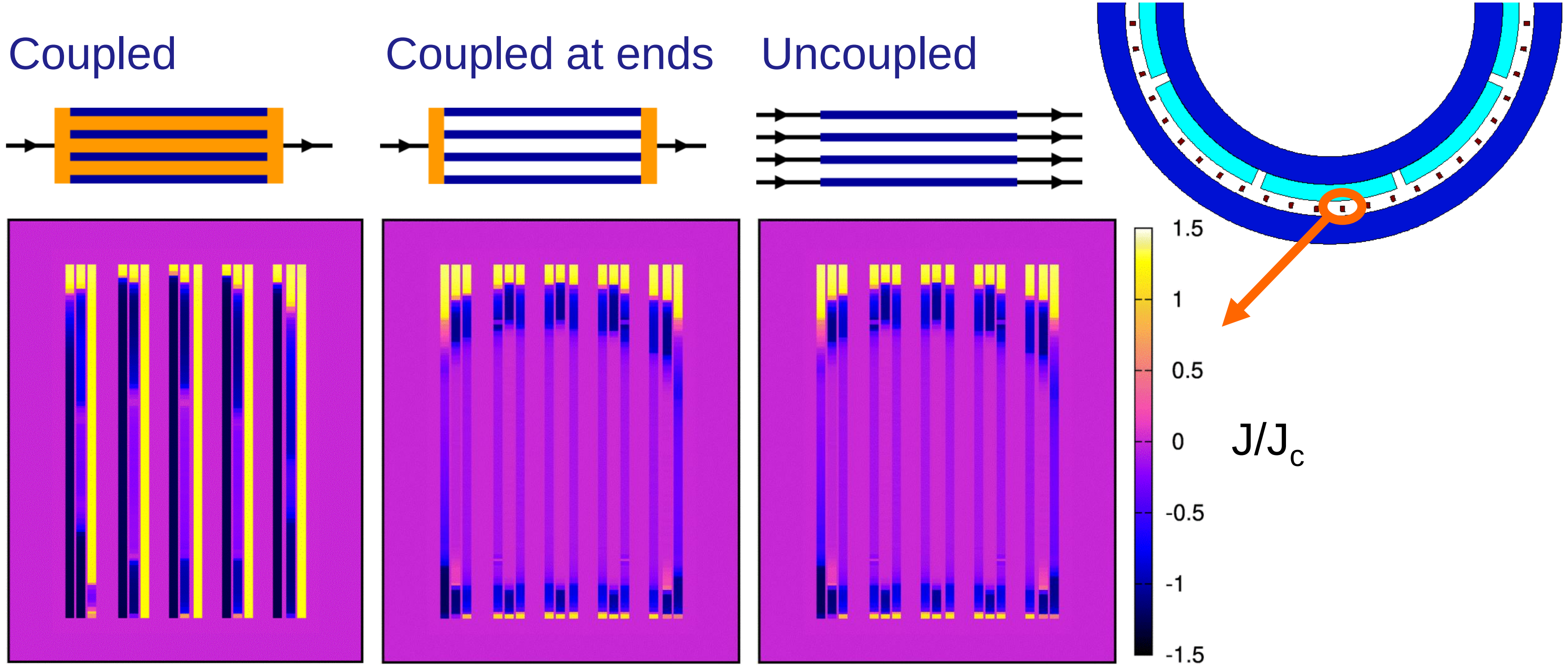

Here, we assume zero resistivity in metal

We can also use realistic resistivity

**S Li today poster**

**M Kapolka tomorrow**

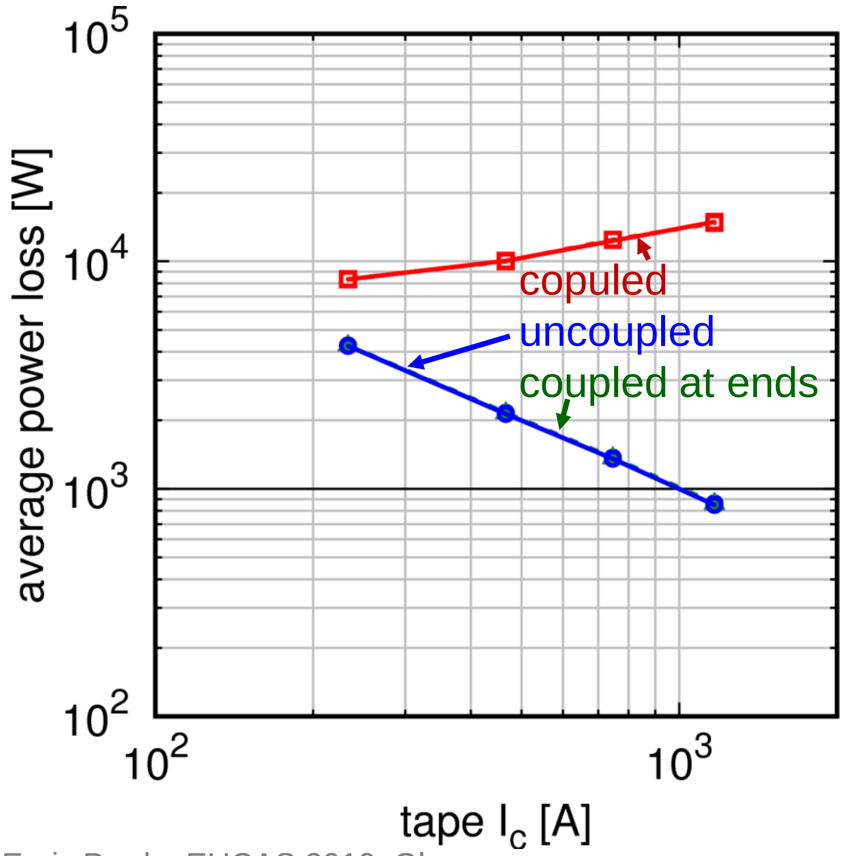
# Coupling configuration changes superconductor currents

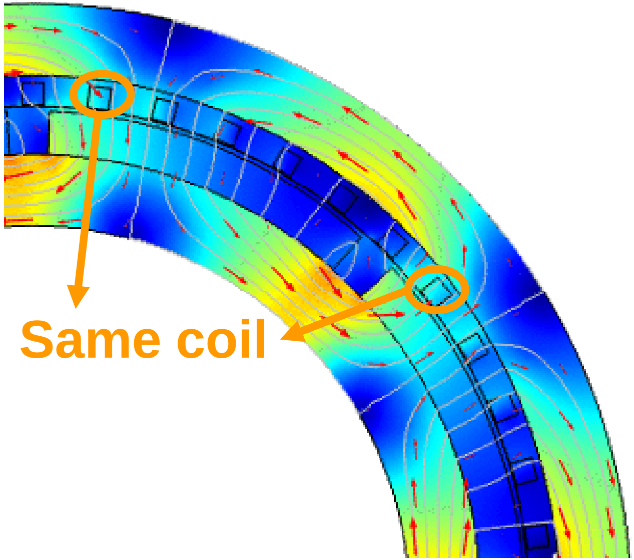



Funded by the European Commission Grant No 723119

# Coupled at ends is the same as uncoupled

Funded by the European Commission Grant No 723119




**Reason:**

symmetric magnetic flux density causes self-transposition

# No need to transpose the cable!

ASuMED

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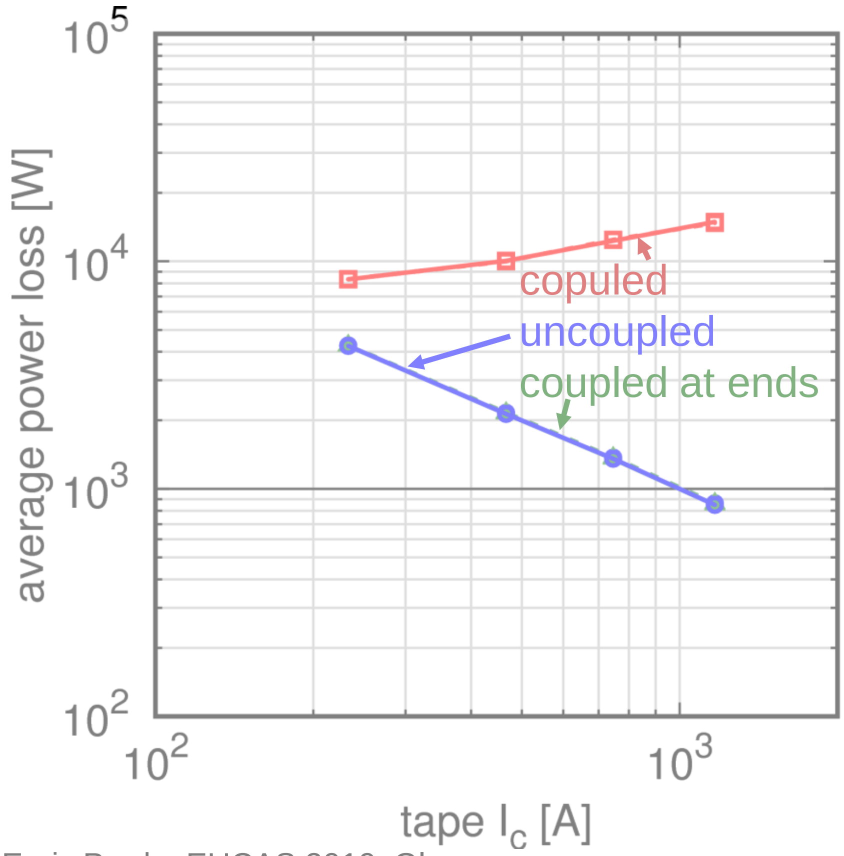
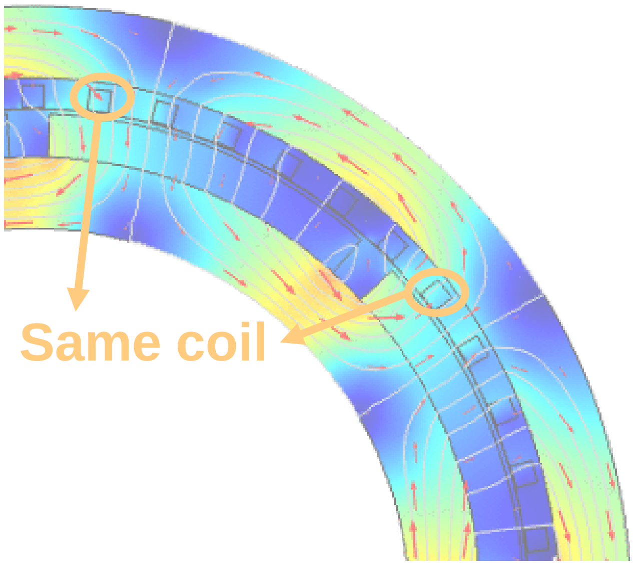
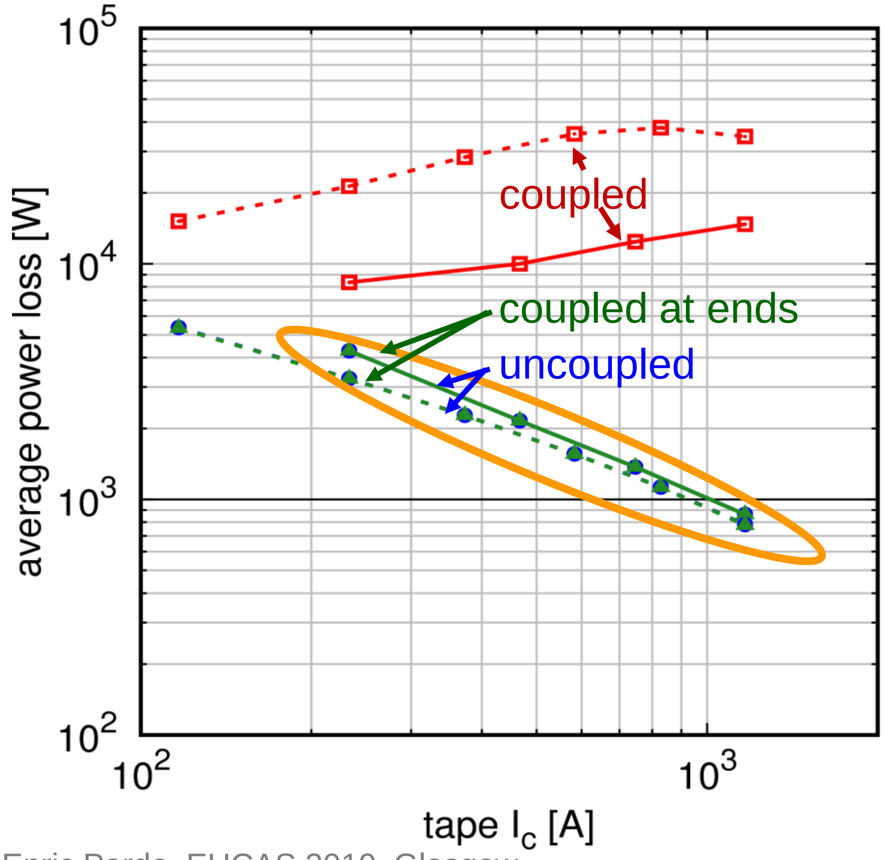


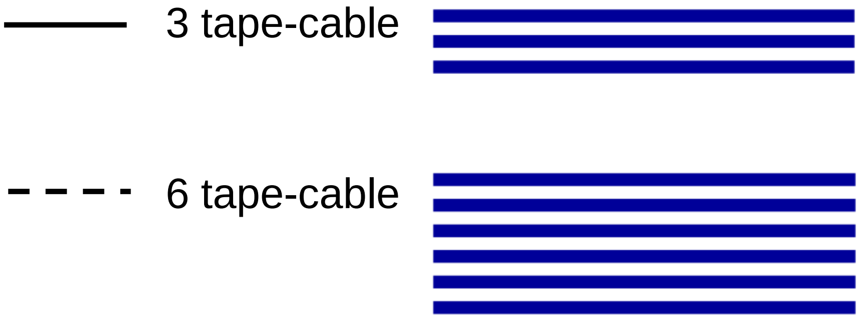




**Reason:**

symmetric magnetic flux density causes self-transposition

# Increasing number of tapes in conductor reduces AC loss




**Cause:**

main AC loss due to perpendicular flux to tape

## Combined numerical method

## AC loss results

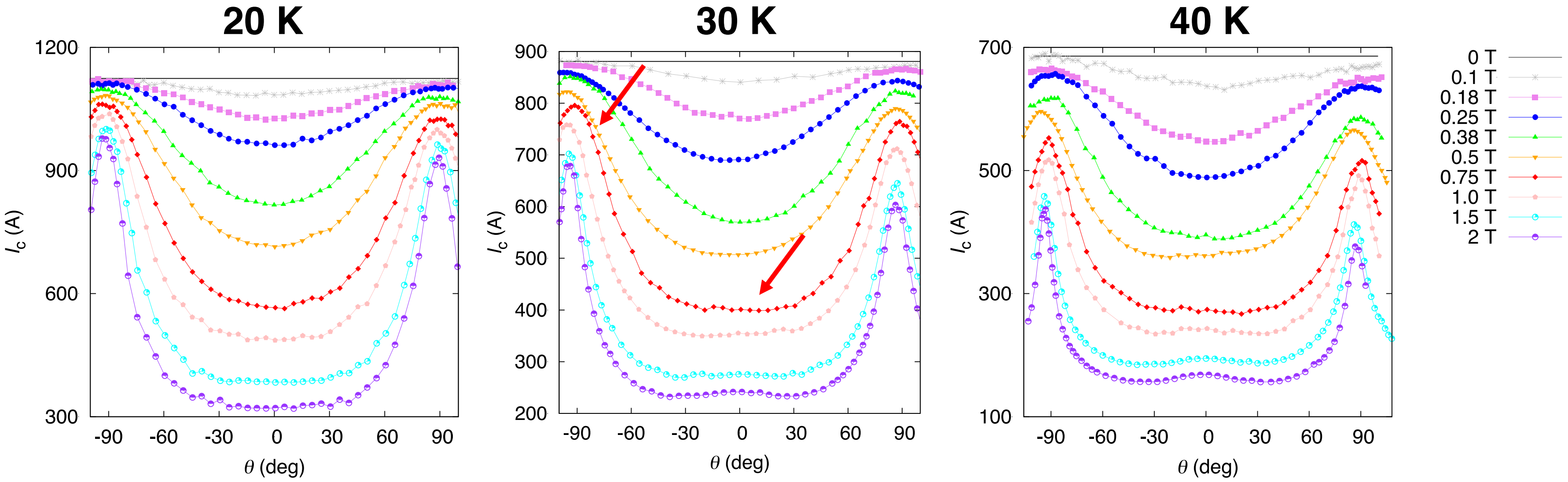
Effect of coupling

Temperature and field dependence

## Novel modelling approach

# 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

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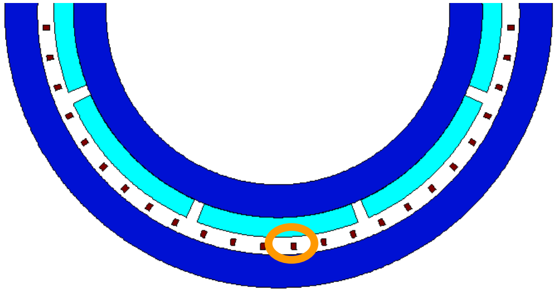

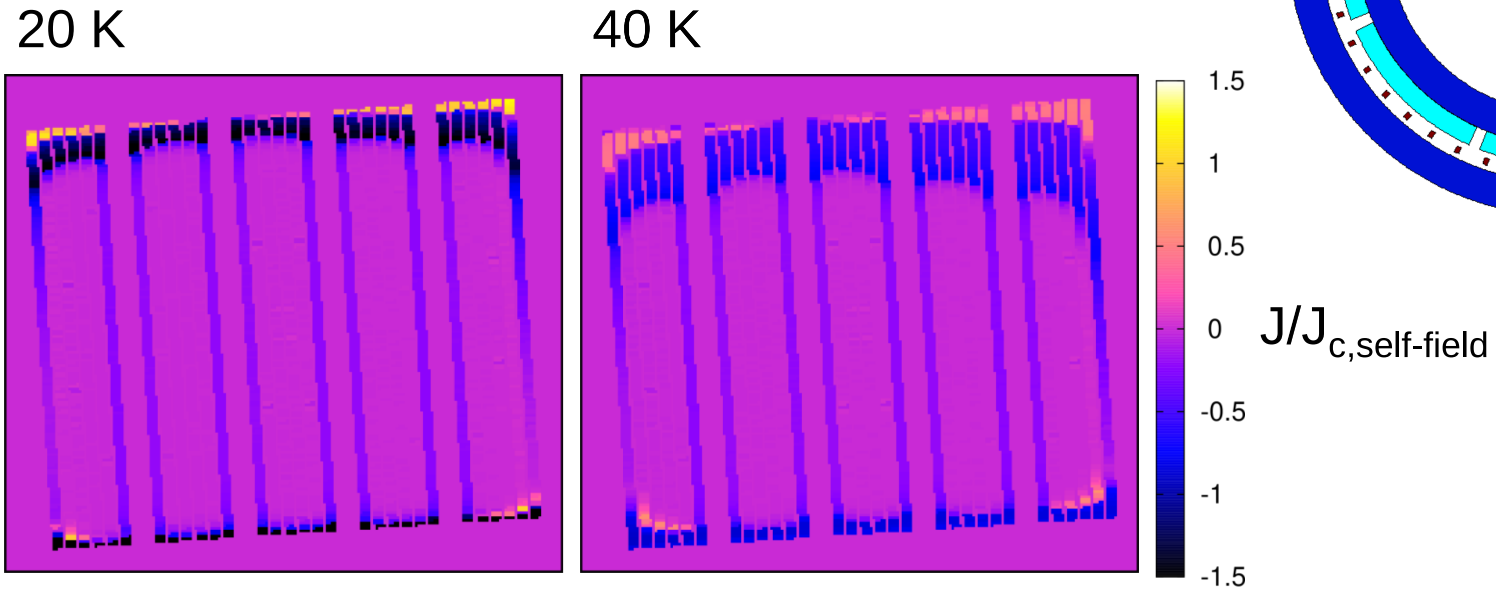


Current density at a particular time step

# Narrower tapes decrease AC loss

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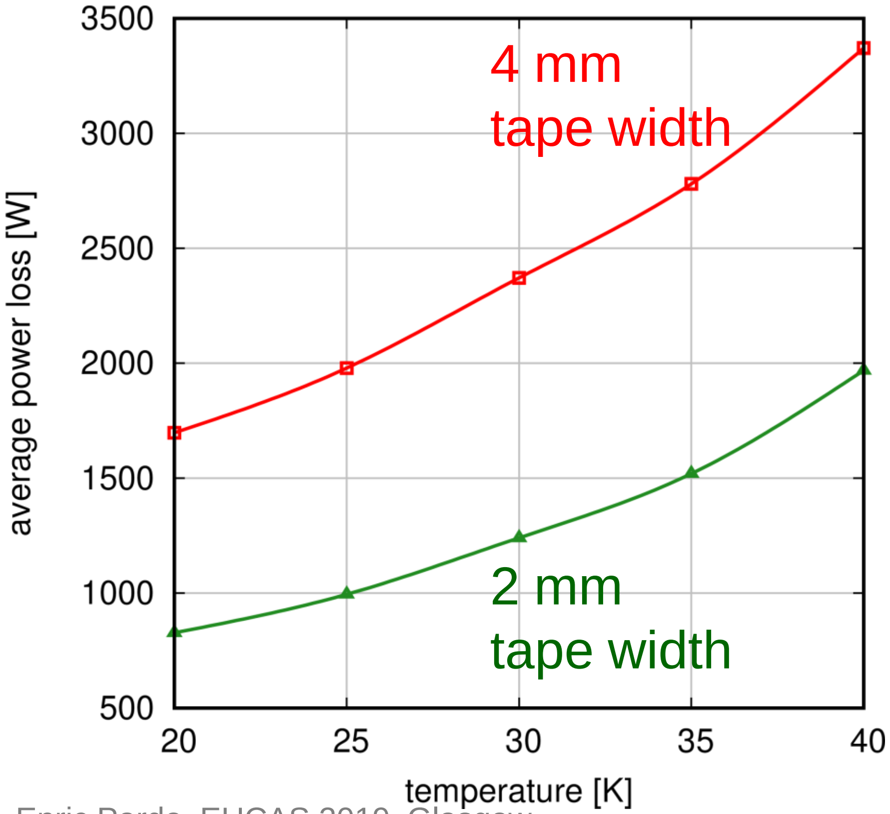


**Narrower tapes with the same $J_c$ are very interesting!**

Combined numerical method

AC loss results

**Novel modelling approach**

# MEMEP also takes ferromagnetic materials into account

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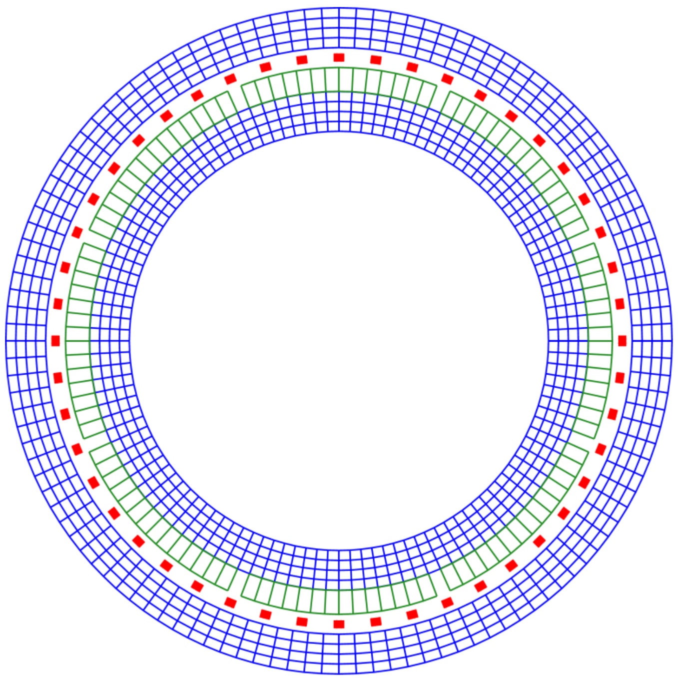
We solve

J in the superconductor

**M** vector in the magnetic material



**No need to solve quantities in the air**

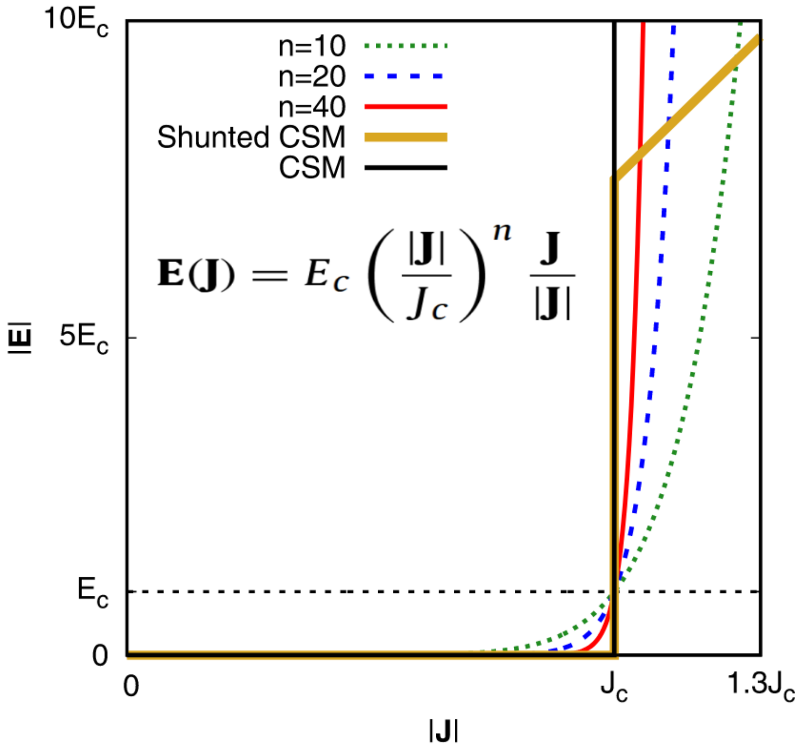
Easy to make rotation

**All interactions taken into account**

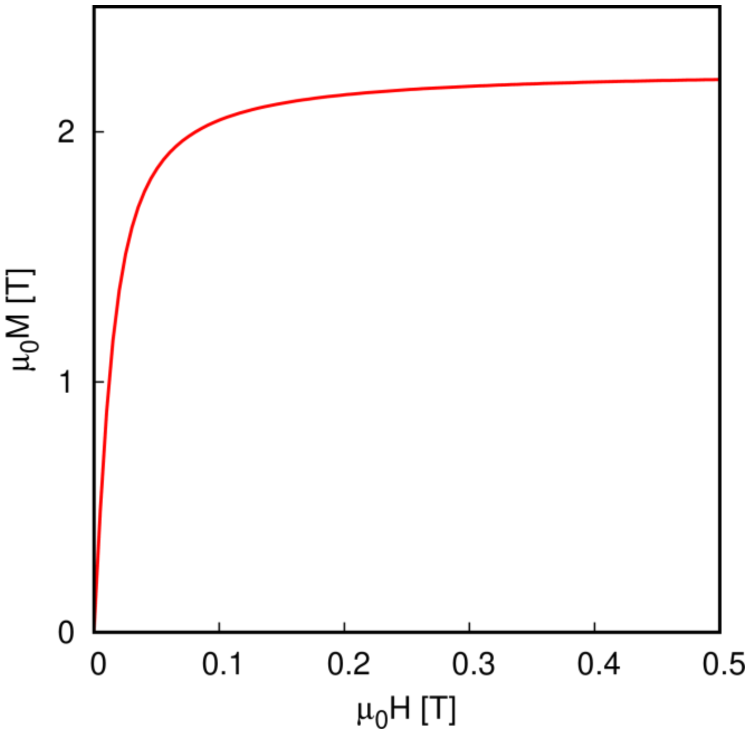
Details in HTS modelling workshop 2018
10.5281/zenodo.1477840

# Non-linear materials

## Superconductor




## Magnetic material






Funded by the European Commission Grant No 723119

# Non-linear eddy currents in superconductor

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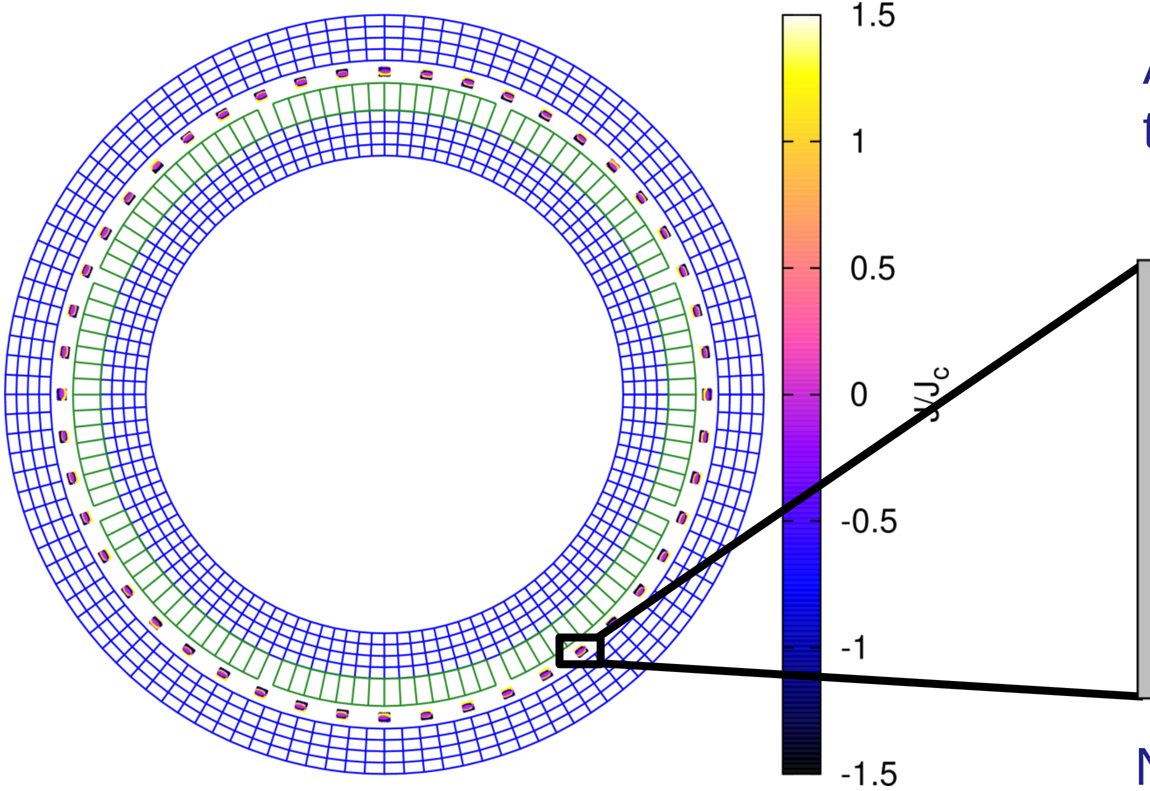
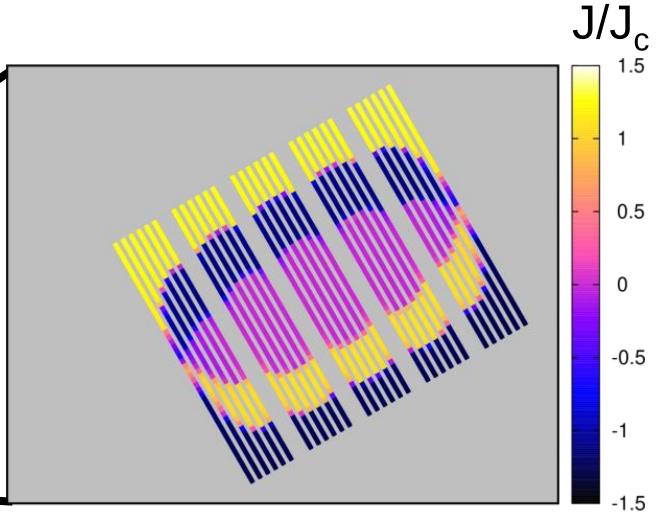



All interactions taken into account




No-load case

# Magnetization in iron and magnets

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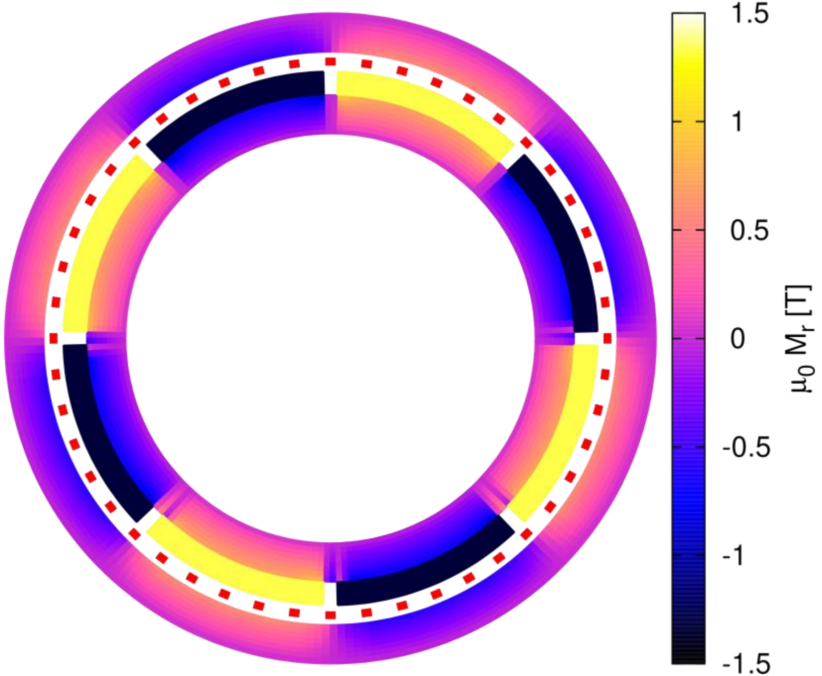
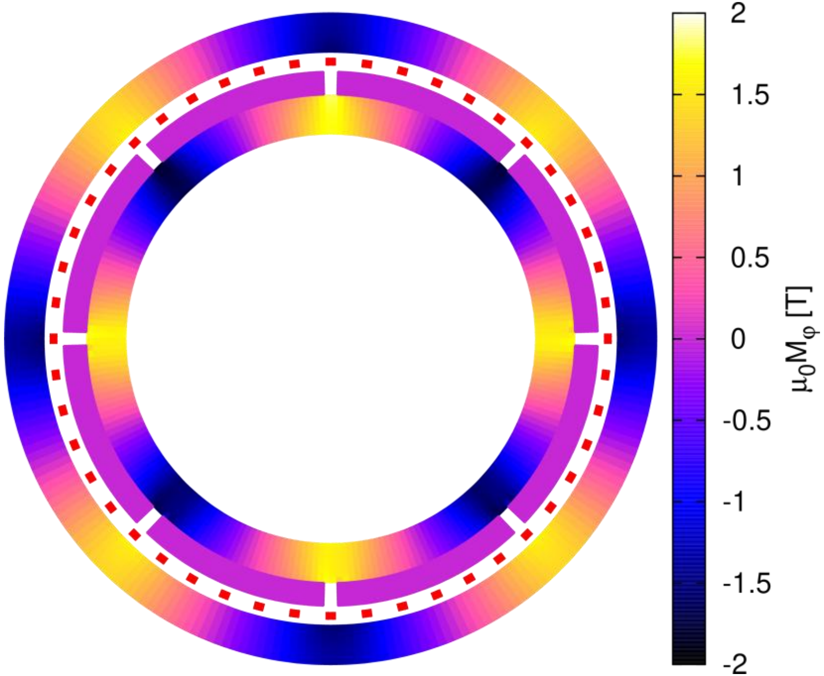
## Radial component: $m_0M_r$ [T]




## Angular component: $m_0M_\varphi$ [T]



# Conclusion

# We modelled AC loss in a distributed stator winding

Combined model with commercial methods and in-house methods

Also full in-house method: MEMEP

**In distributed stator windings you do not need to transpose multi-tape conductors**

**Narrower tapes of the same $J_c$ decrease AC loss**

# We can also model

**Superconducting rotor** made of

- Stacks of tapes
- Bulks
- Coils

**Full superconducting motor**

# Thank you for your attention!

# Would you like to know more?

enric.pardo@savba.sk

# Coupled at ends
# is the same as uncoupled

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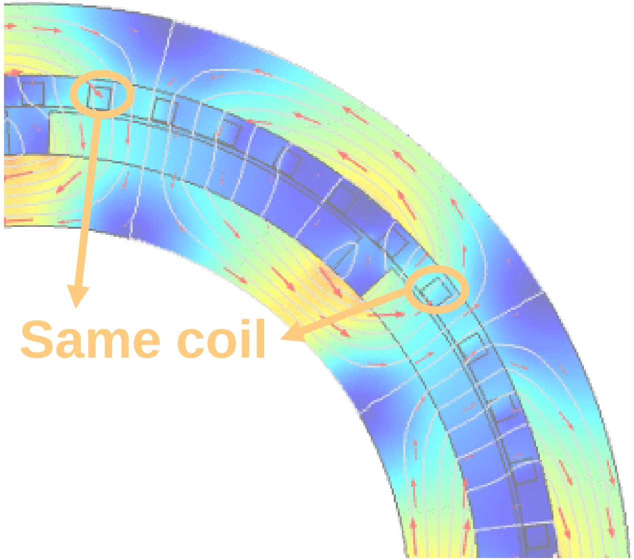
**No need to transpose the cable!**

**What happens
if there are imperfections
in the winding?**




**Reason:**

symmetric magnetic flux density
causes self-transposition

# AC loss is not sensitive to stator coil imperfections

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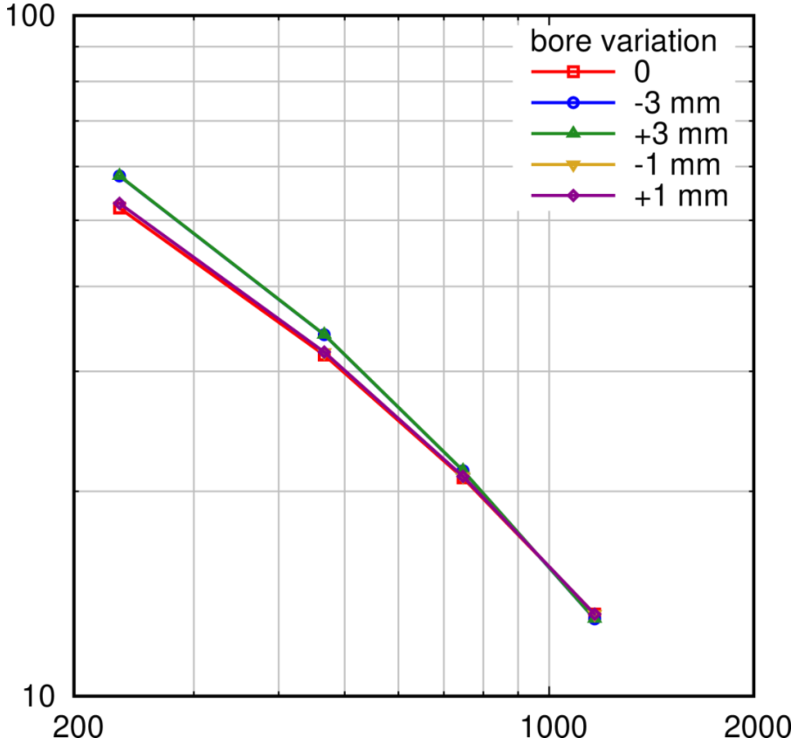
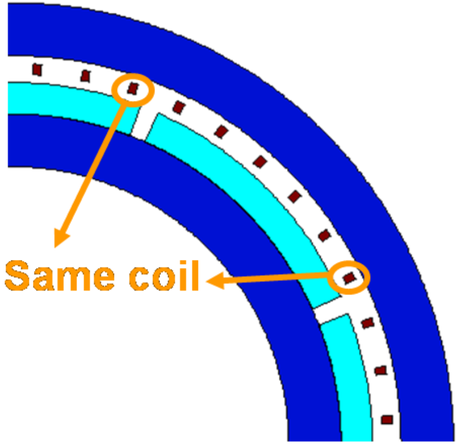
AC loss per coil [W]




tape critical current [A]

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