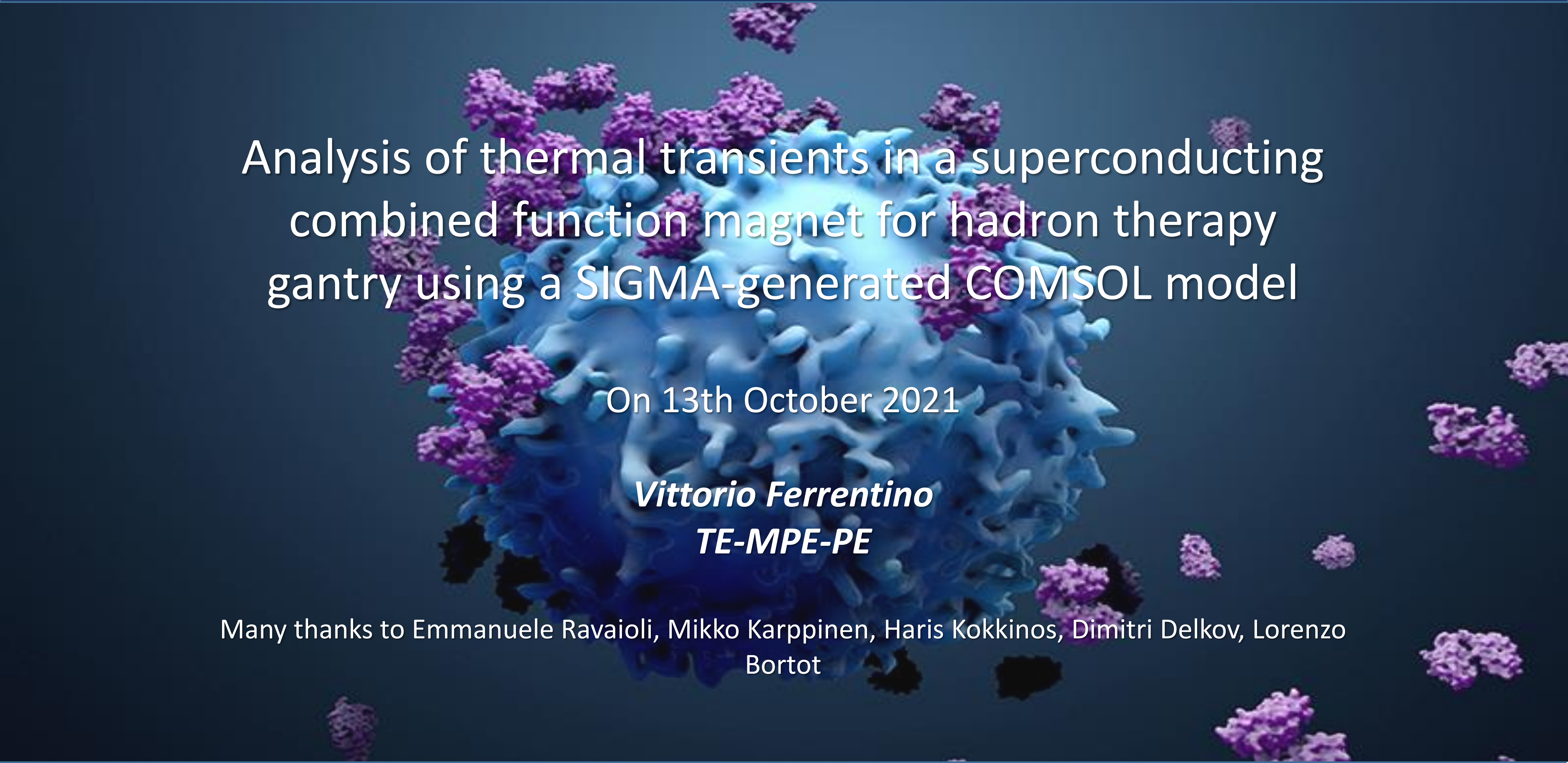


Analysis of thermal transients in a superconducting combined function magnet for hadron therapy gantry using a SIGMA-generated COMSOL model

On 13th October 2021

Vittorio Ferrentino
TE-MPE-PE

Many thanks to Emmanuele Ravaioli, Mikko Karppinen, Haris Kokkinos, Dimitri Delkov, Lorenzo Bortot

Goals and contents of the presentation

Goal

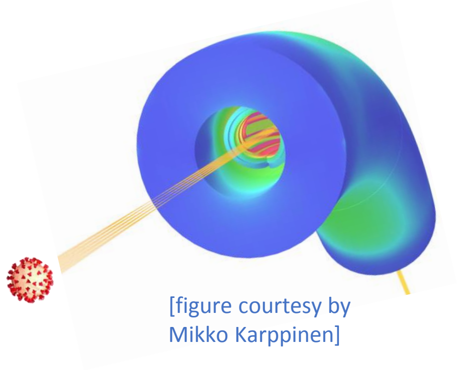
Powering cycles simulations: assess the impact of transitory losses and cooling features on the thermal transient. Demonstrate that the proposed design does not result in excessive coil temperature (above 6 [K]) during powering, even under very conservative assumptions.

Software used

- **STEAM-SIGMA** to generate the COMSOL magnet model
- **COMSOL© Multiphysics v5.3a** for the powering cycles simulations and thermal transient analysis

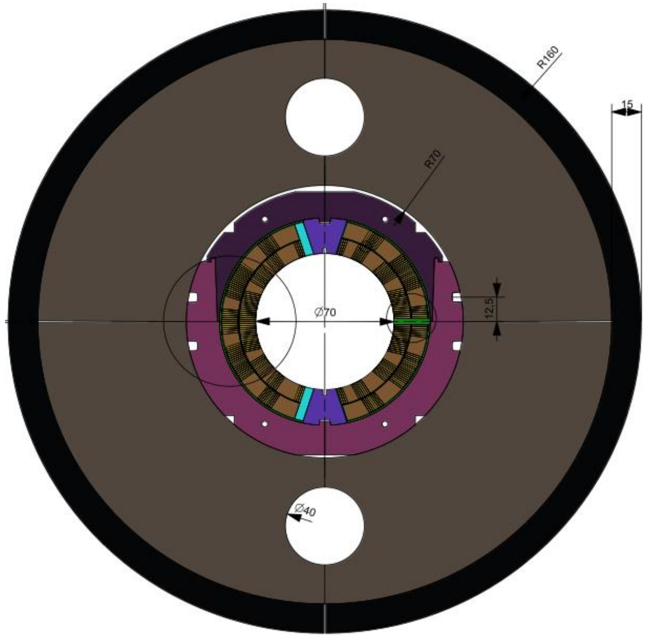
Contents

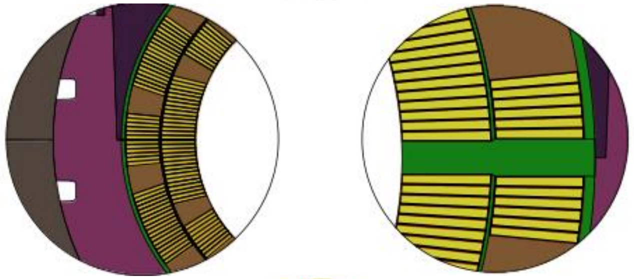
- **Magnet and power cycle features and the SIGMA-built model**
- Cases analyzed and assumptions
- Reference case analysis
- Worst case: higher losses
- Conclusions

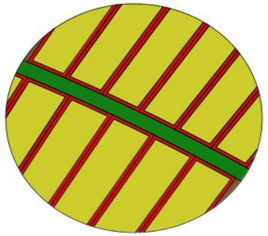


[figure courtesy by Mikko Karppinen]

Magnet cross-section and features





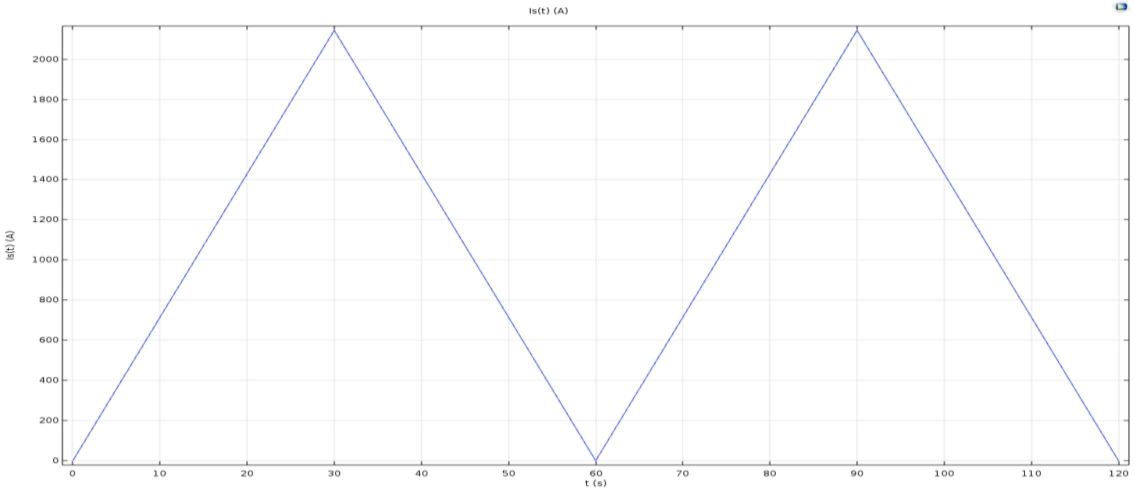


[figures courtesy by Mikko Karppinen]

Legend:

- 🟨 Coil
- 🟥 Insulation
- 🟫 Copper wedges
- 🟪 Collar
- ⬛ Iron joke

- Operating temperature: 4.5 [K]
- Nominal current: 2144 [A]
- Nominal magnetic field in the magnet aperture: 3.3 [T]
- RRR Cu_wedges: 100
- f_ro_eff standard value*: 1
- Hysteresis loss: uniform in space and constant in time
- Power cycle



- Power cycle 60 [s] long
- Rise time 30 [s]
- Peak value = Nominal current
- Magnetic field change during the ramp = 0.1 [T/s]

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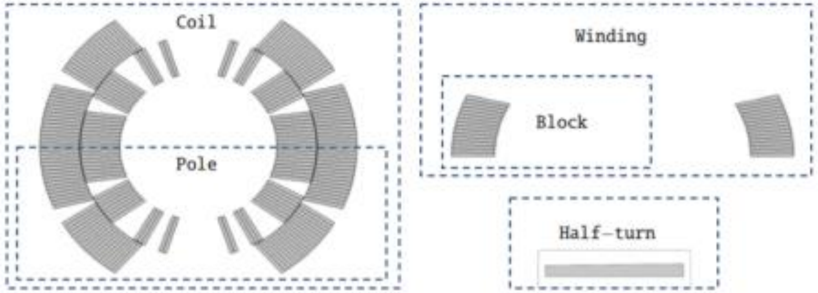
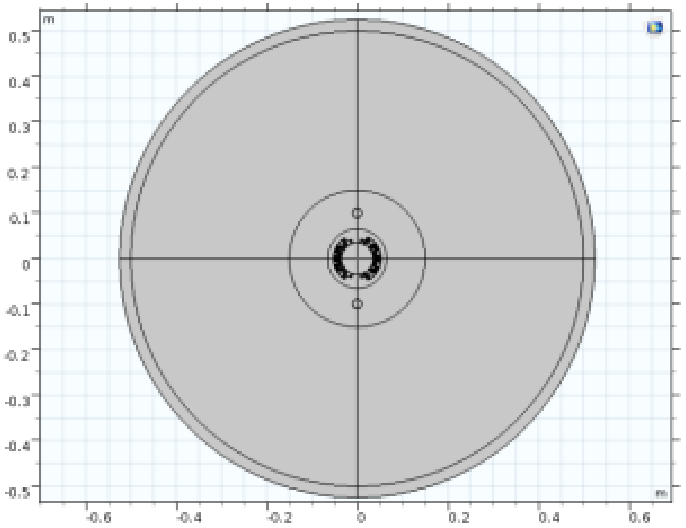
*f_ro_eff is the effective transverse resistivity between the filaments

SIGMA-built model

- **STEAM-SIGMA** is a Java-written tool which **automatically generates complex magnet models**.
- Possibility of **inserting material property functions in the COMSOL model**, which are imported in the COMSOL model as *.dll files* (dynamically linked libraries) provided as a compiled C-code. An external database for the iron BH-curve is available as a *.txt file*.
- Geometrically, **STEAM-SIGMA is based on basic geometrical shapes** (points, straight lines, arcs, ellipse sectors, circumferences), which allow to build more complex geometries. The geometrical classes related to the coil of the magnet are built by **block** (hyper-area divided into half-turns), **winding** (array of HyperAreas, composed by two stacks of adjacent half-turns in a magnet coil having opposite current directions), **pole** (a set of windings forming a magnet pole) and finally the **coil**, defining the magnet coil of a single cross-section.
- Running the STEAM-SIGMA model, the COMSOL model of a specific magnet is generated as well as the magnetic field maps.





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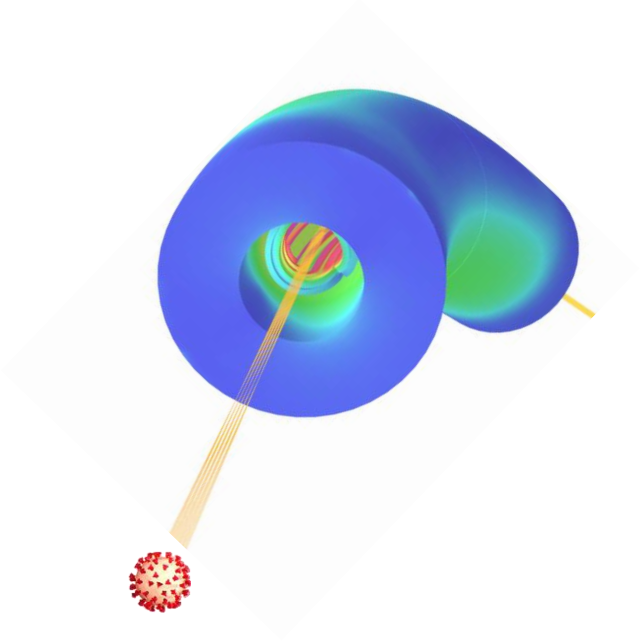
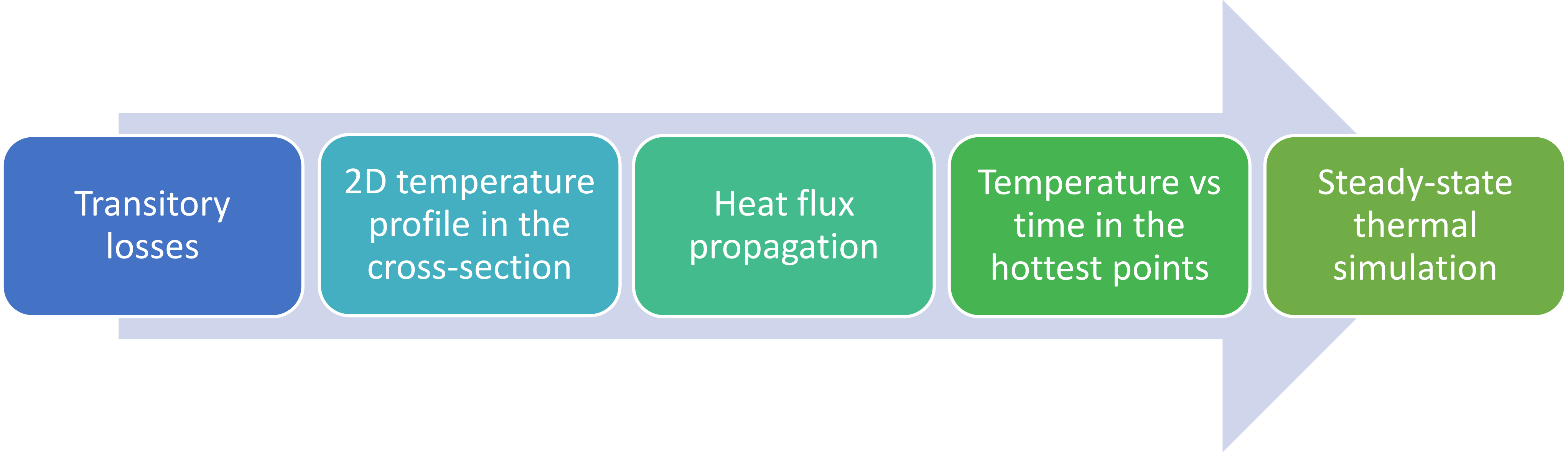


[figure courtesy by Mikko Karppinen]

What will we analyze?



Transitory losses

2D temperature profile in the cross-section

Heat flux propagation

Temperature vs time in the hottest points

Steady-state thermal simulation

Simulations performed and assumptions

Simulations	IFCL+ISCL	Hysteresis loss	Cu_wedg loss	Coil – collar contact	Yoke – collar contact
1 Reference case	Reference → f_ro_eff=1	Reference → 201.8 $\left[\frac{W}{m^3}\right]$	Reference → RRR_Cu_wedges = 100	Reference → Therm_cond_gr_insul = SIGMA	Reference → Thermal resistance = 12.56 $\left[\frac{Km^2}{W}\right]$
2. Worst case: higher losses	Reference*3	Reference*4	Reference	Reference/4	Reference

Hysteresis losses

- ROXIE
- STEAM-LEDET

IFCL+ISCL

- COMSOL
- STEAM-LEDET

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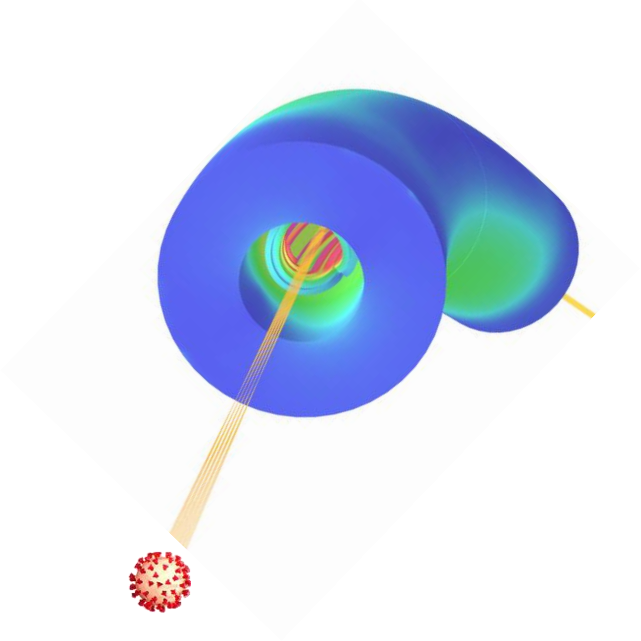
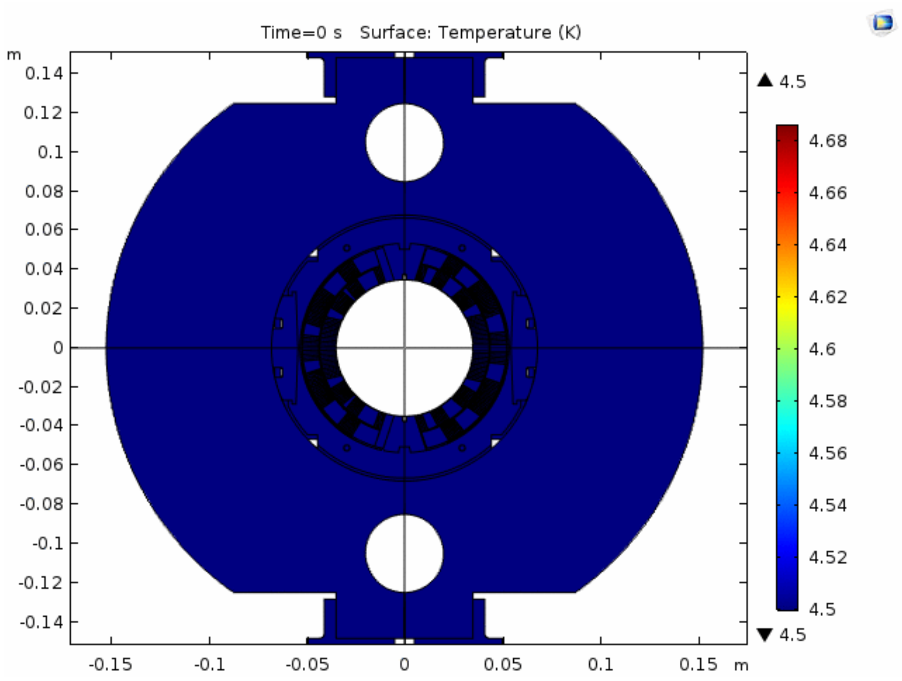


[figure courtesy by Mikko Karppinen]

Reference case: thermal transient in the magnet

Simulations	IFCL+ISCL	Hysteresis loss	Cu_wedg loss	Coil – collar contact	Yoke – collar contact
1 Reference case	Reference → f_ro_eff=1	Reference → 201.8 $\left[\frac{W}{m^3}\right]$	Reference → RRR_Cu_wedges = 100	Reference → Therm_cond_gr_insul = SIGMA	Reference → Thermal resistance = 12.56 $\left[\frac{Km^2}{W}\right]$

2D temperature profile

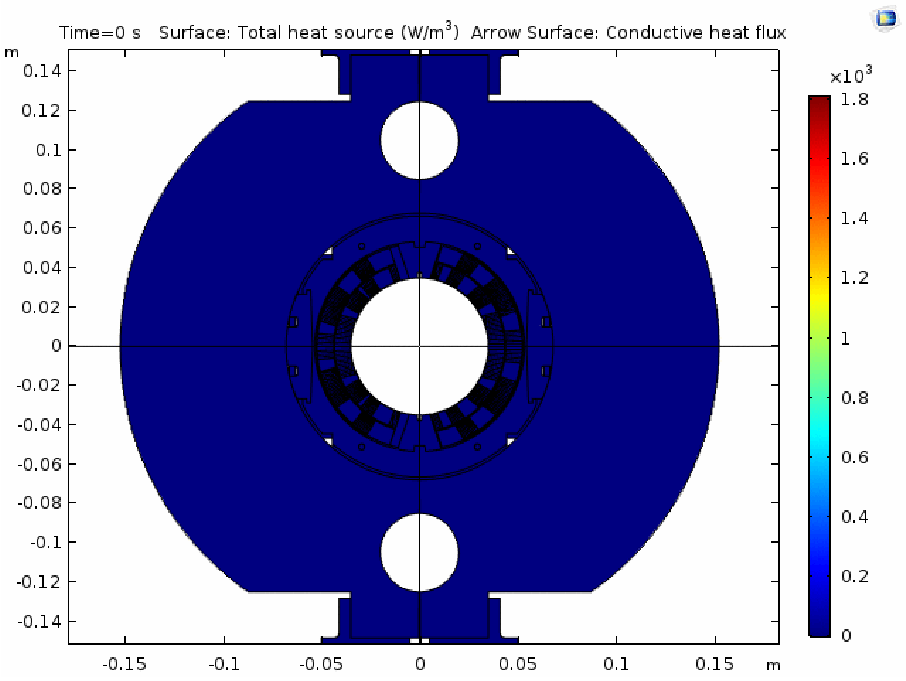


Fourier equation:

$$q = -k\nabla T \quad \left[\frac{W}{m^2}\right]$$

- q is the heat flux
- T is the temperature
- ∇T is the temperature gradient
- K thermal conductivity

Heat flux and heat source

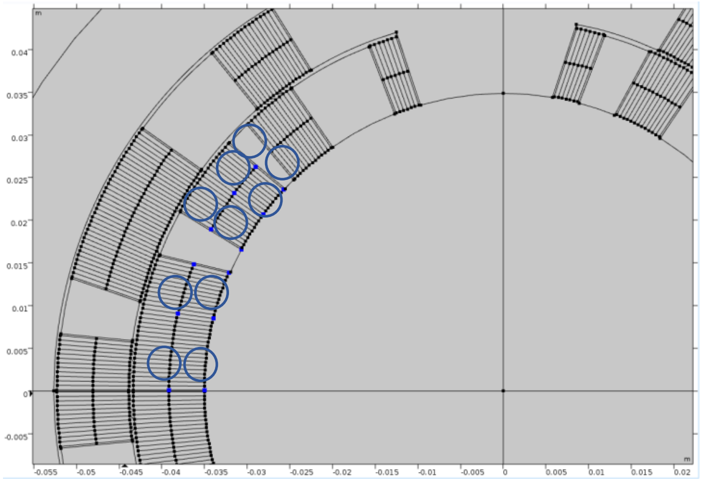


At the beginning the heat is deposited just in the coil and collar, then it propagates towards the external part of the magnet and the temperature starts to increase there (slightly in the yoke). The two holes are the thermal sinks for the magnet and they basically take all the heat generated in it, remaning at the initial temperature. Arrows directions and size give heat flux direction and amplitude.

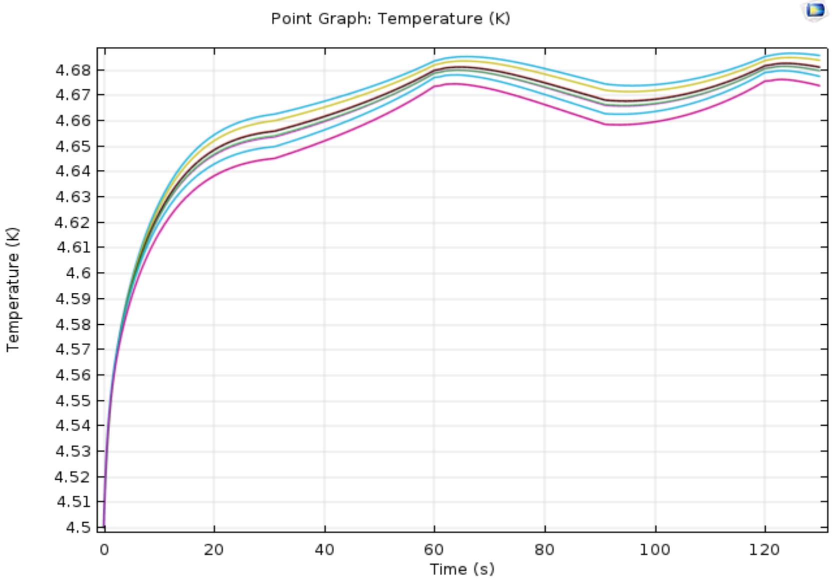
Reference case: temperature vs time in the hottest points

Simulations	IFCL+ISCL	Hysteresis loss	Cu_wedg loss	Coil – collar contact	Yoke – collar contact
1 Reference case	Reference → f_ro_eff=1	Reference → 201.8 $\left[\frac{W}{m^3}\right]$	Reference → RRR_Cu_wedges = 100	Reference → Therm_cond_gr_insul = SIGMA	Reference → Thermal resistance = 12.56 $\left[\frac{Km^2}{W}\right]$

Point which temperature is plotted (blue ones)



Temperature vs time



After a fast transient, the temperature drop is between 4.685 [K] and 4.675 [K] during the power cycle

The peak temperature is largely below 6 [K]

The peak temperature at the end of the second power cycle (120 [s]) is the same of the peak temperature after 60 [s]. The system reaches regime after 2 powering cycles

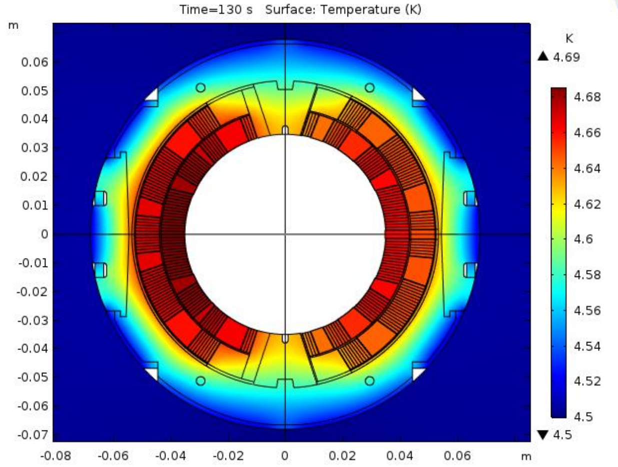
In 900 [s] (15 power cycles) the temperature enhancement is very low, about 0.1 [mK].

However, considering a continuous operation of the magnet, this enhancement could create problems, if it never stops. Indeed, if the yoke continues heating up, the cooling effect for the coil and collar will be lower

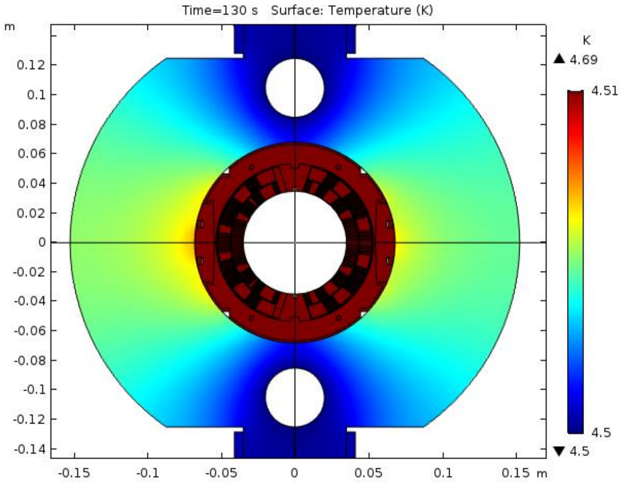
.. To be sure that sooner or later the system reaches a steady-state condition, a solution is to perform a steady-state simulation.

Steady-state thermal simulation

Time dependent simulation



4.69 [K]



4.69 [K]

Assumptions for steady state thermal simulation

Hysteresis loss constant in time and uniform in space, the reference ones

8.97 [J/m]

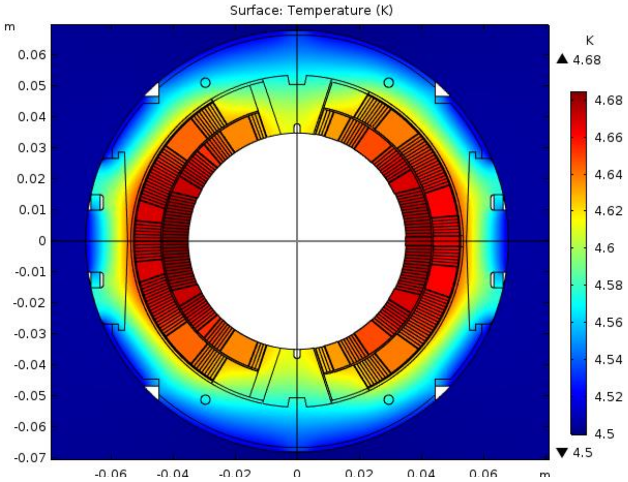
IFCL+ISCL constant in time and uniform in space, calculated with surface integration in 60 [s], divided by 60 [s] and divided by the area of the coil in the cross-section

8.98 [J/m]

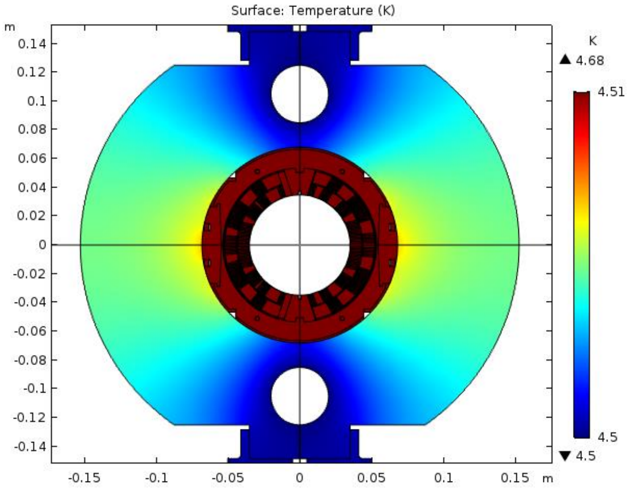
Wedges loss constant in time and uniform in space, calculated with surface integration in 60 [s], divided by 60 [s] and divided by the area of the wedges in the cross-section

With this scale, all the dark red parts are at temperature higher than 4.51 [K]

Steady-state simulation



4.69 [K]



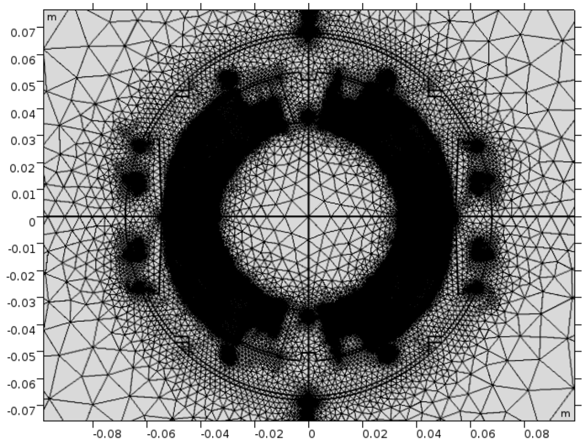
4.69 [K]

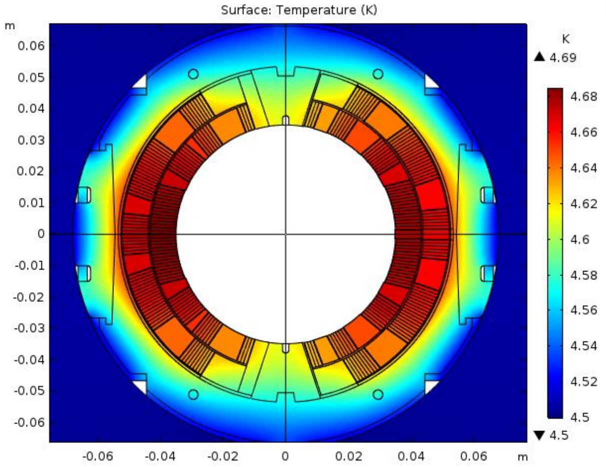
The steady-state thermal simulation provides exactly the same results of the time dependent simulation. This result supports the assumptions done. **The system reaches a regime.**

Mesh sensitivity analysis

All the results shown are valid if they do not change by scaling (or changing) the mesh. In order to prove it, let's set an extremely fine mesh.

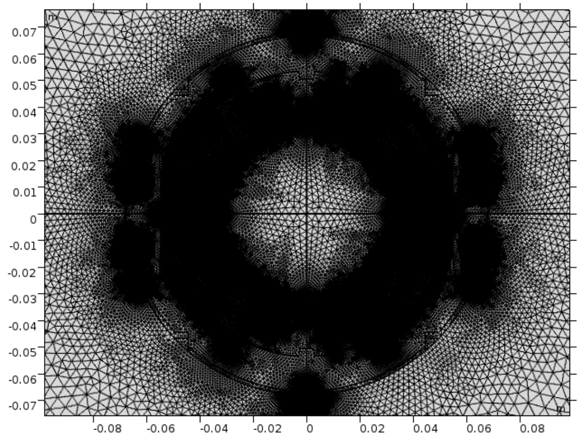
Mesh size COMSOL: normal

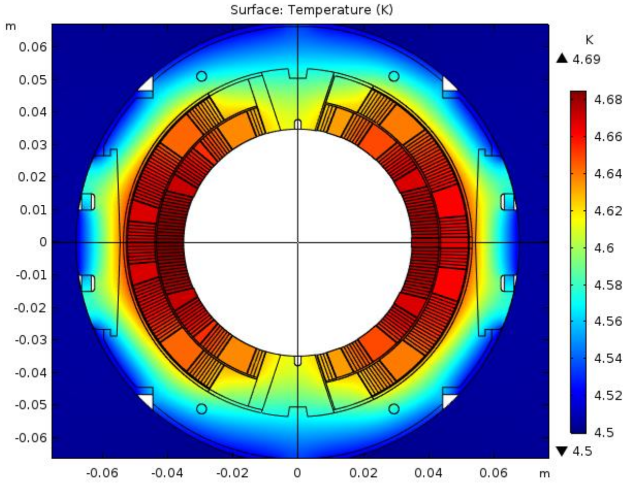




165558 domains and 30589 boundary elements

Mesh size COMSOL: extremily fine





359286 domains and 34133 boundary elements

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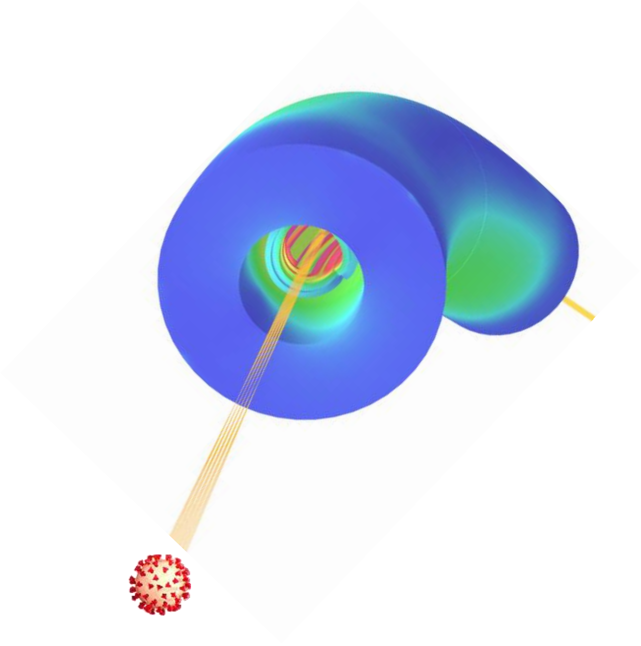
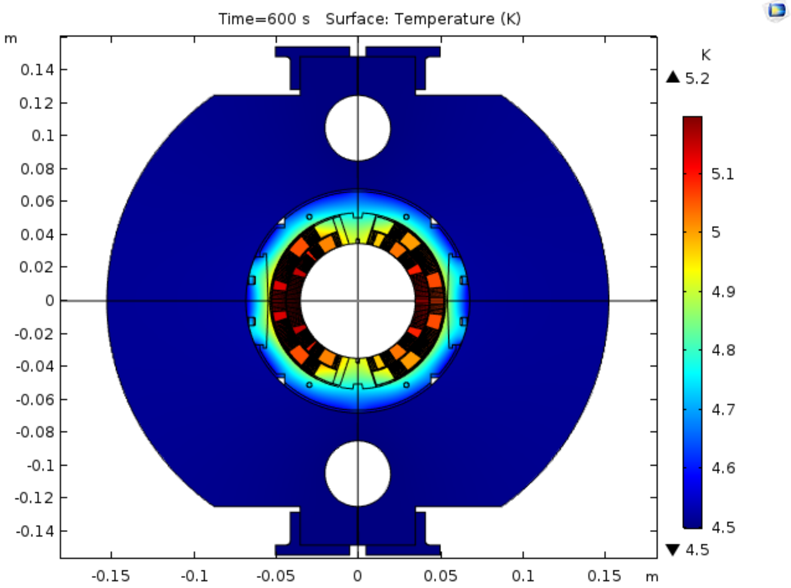


[figure courtesy by Mikko Karppinen]

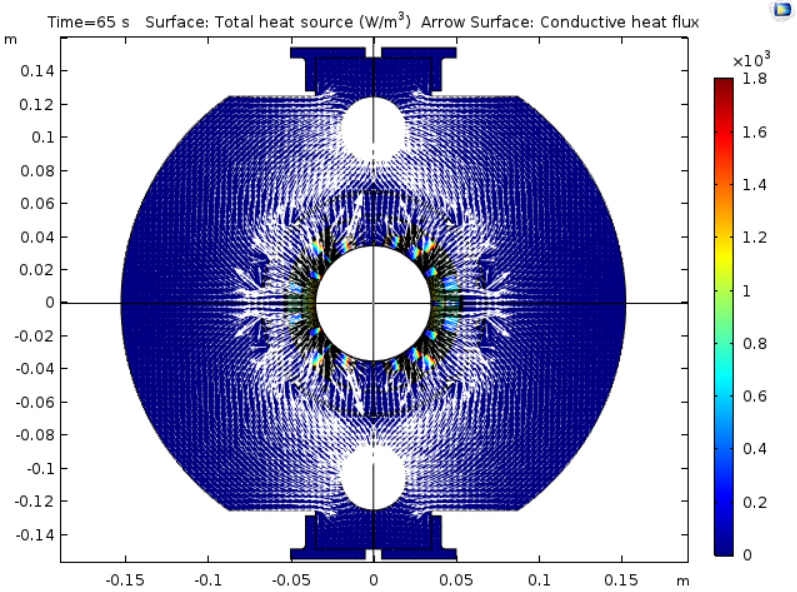
Worst case analysis: simulation under very conservative assumptions

Simulations	IFCL+ISCL	Hysteresis loss	Cu_wedg loss	Coil – collar contact	Yoke – collar contact
2. Worst case	Reference*3	Reference*4	Reference	Reference/4	Reference

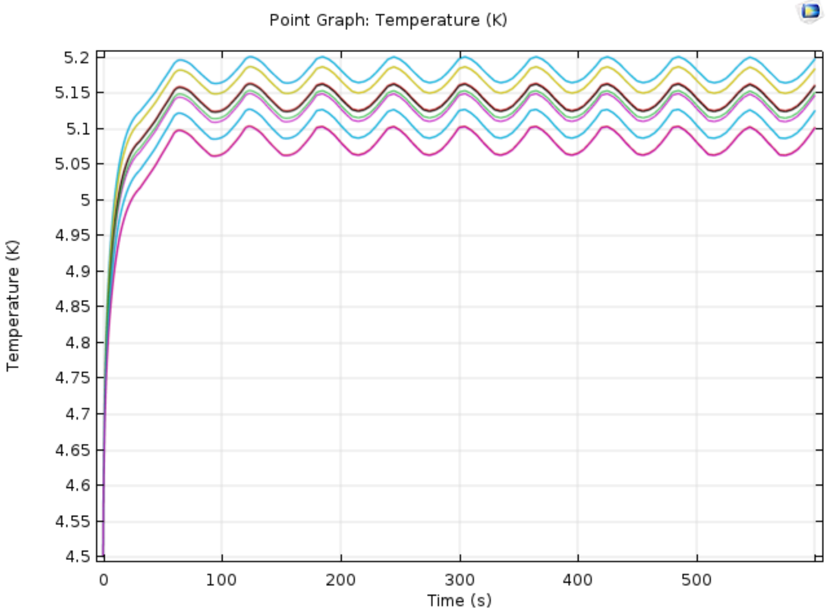
2D temperature profile



Heat flux and heat source



Temperature vs time

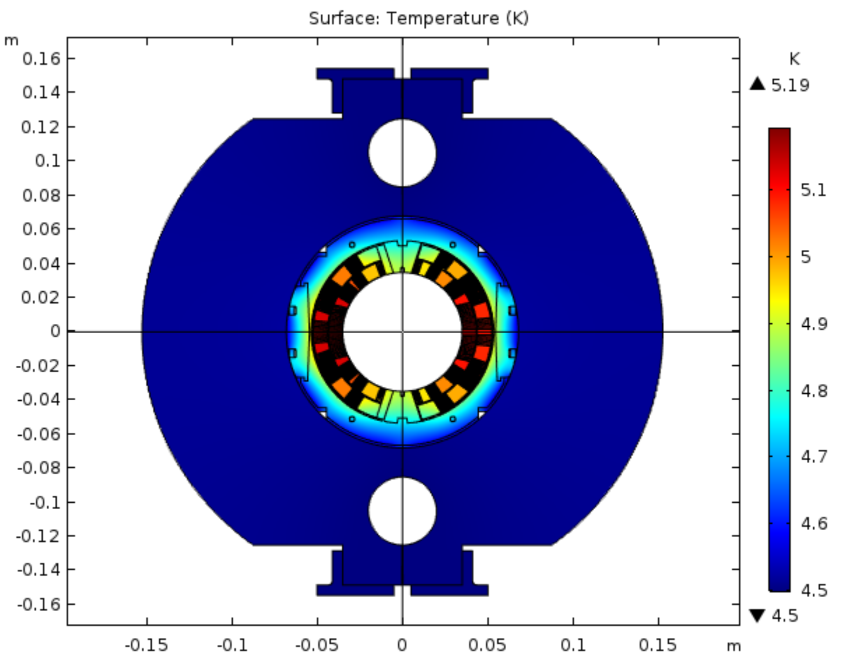


The temperature at the end of the first power cycle (60 [s]) is still increasing, then it reaches a regime. The transient is slower in this case and the peak temperature is 5.2 [K], higher than the reference case. This makes sense for the assumptions done about the losses.

Worst case analysis: Steady-state thermal simulation

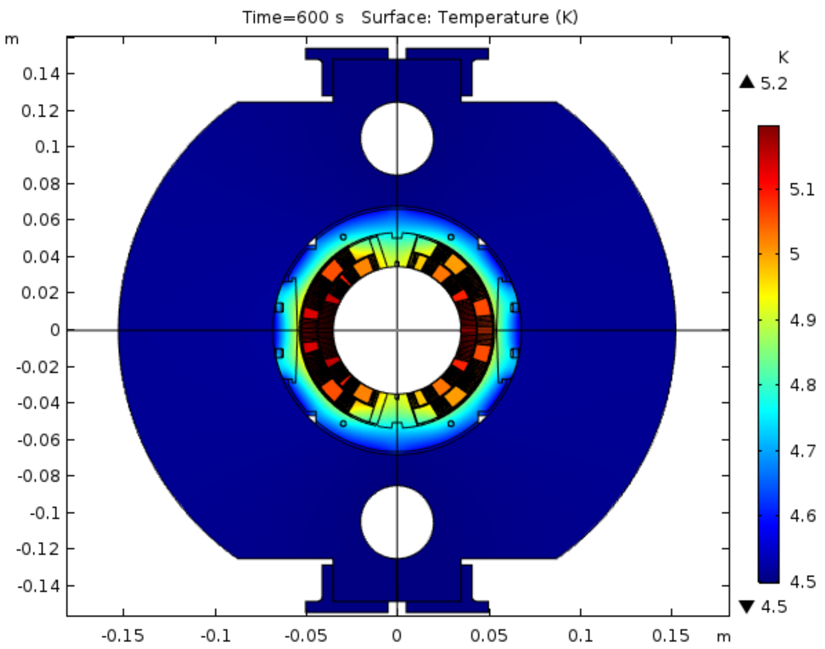
Simulations	IFCL+ISCL	Hysteresis loss	Cu_wedg loss	Coil – collar contact	Yoke – collar contact
2. Worst case	Reference*3	Reference*4	Reference	Reference/4	Reference

Steady-state thermal simulation



5.19 [K]

Time dependent simulation



5.20 [K]

The difference is of 0.01 [K]

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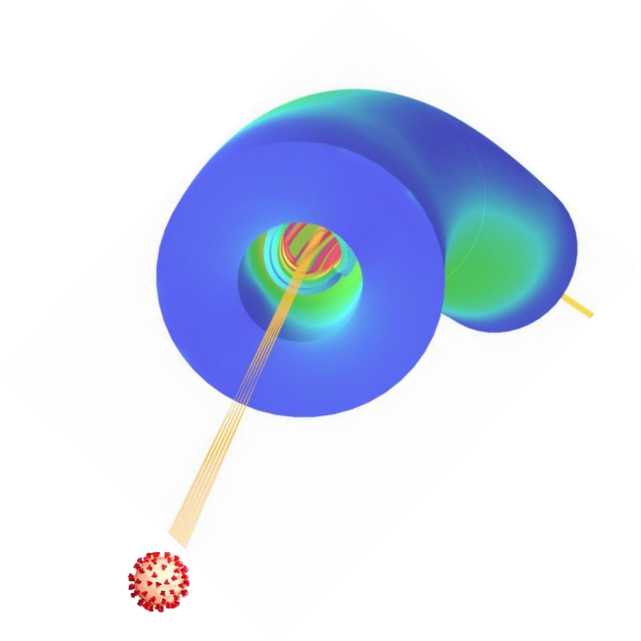
- Quench protection
- **Conclusions**



[figure courtesy by Mikko Karppinen]

Conclusions

Powering and thermal transient analysis

Software used: **COMSOL© Multiphysics v 5.3a**

For powering, in both cases analyzed (reference case and higher losses case) the temperature is below 6 [K] and the steady-state thermal simulations prove that the magnet reaches a regime in a time window comparable to the one of a time-dependent simulation.

Therefore, these simulations in COMSOL show that the magnet actually does not need any special feature to improve the cooling

COMSOL - Powering	Peak temperature [K]	Time to go to regime [s]	Losses in the coil (IFCL, ISCL, hysteresis) [W]	Losses in copper wedges [W]
1.Reference case *	4.69	≅ 60	1.02	0.26
2.Worst case	5.20	≅120	3.75	0.26

To add …Scaling from Discorap gives a total of roughly **0.88 W** for eddy current (collars, collaring keys, iron) and hysteresis (iron) losses in the cold mass for the power cycle

Thank you for your attention