



Using Finite Element Modelling to Improve Transcranial Magnetic Stimulation Devices

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Who are Magstim?

- Since 1990, Magstim has provided the means for neuroscientists to work with the human brain in awake subjects by manufacturing and supplying state-of-the-art clinical and research instruments.
- Researchers use Magstim stimulators to investigate the connectivity of the brain, with results that have implications for the diagnosis and treatment of Multiple Sclerosis, Central Motor Disorders, Motor Neurone Disease and Spinal Injury.
- Clinical applications for patients suffering from severe depression have shown that rTMS is an effective alternative where pharmaceutical options cannot help.
- Magstim also manufactures the Neurosign range of intra-operative monitors and accessories, that are routinely used by ENT (Ear, Nose and Throat) surgeons to protect vital nerves during complex surgery.

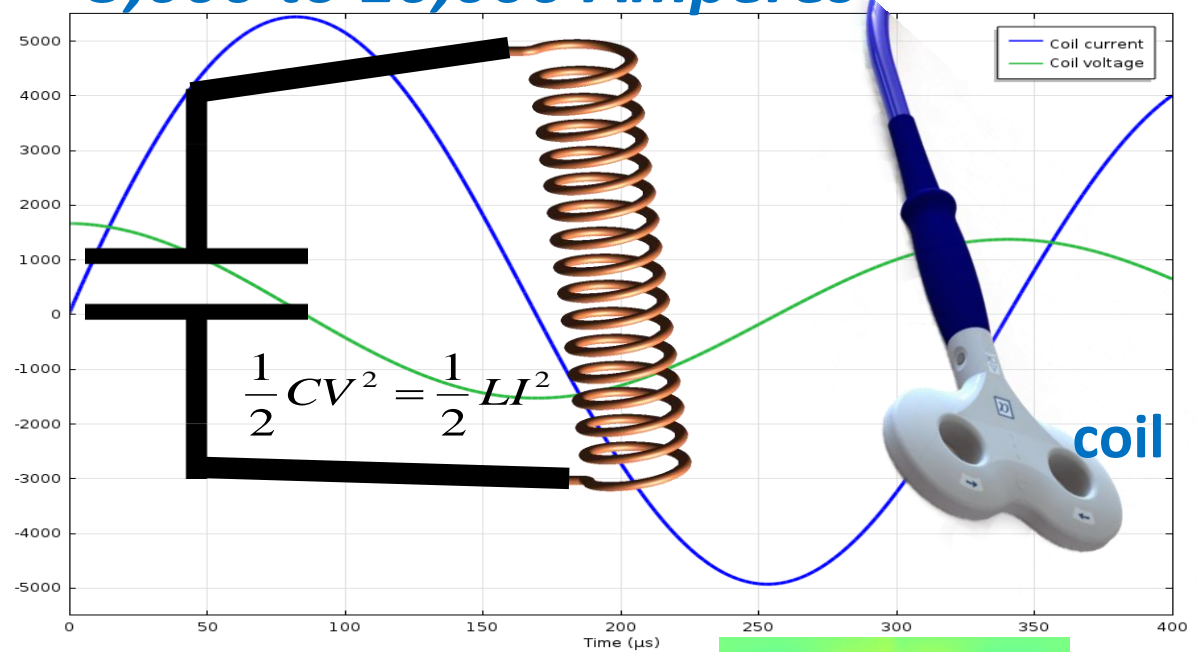


What is a TMS System?

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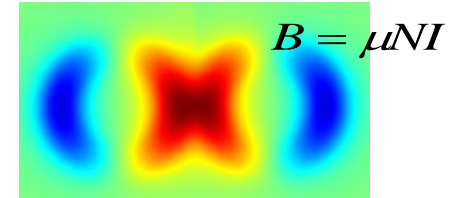


5,000 to 10,000 Amperes



280 μs to 500 μs pulses

Magnetic fields ranging from 1 to 3 Tesla



How does TMS cause stimulation?



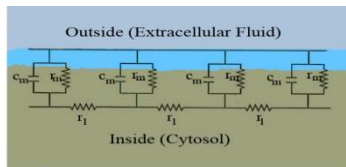
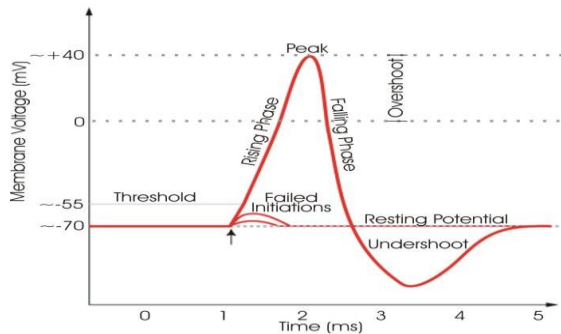
$$\nabla \wedge E = -\frac{\partial B}{\partial t}$$



$$J = \frac{i}{A} = \sigma E$$



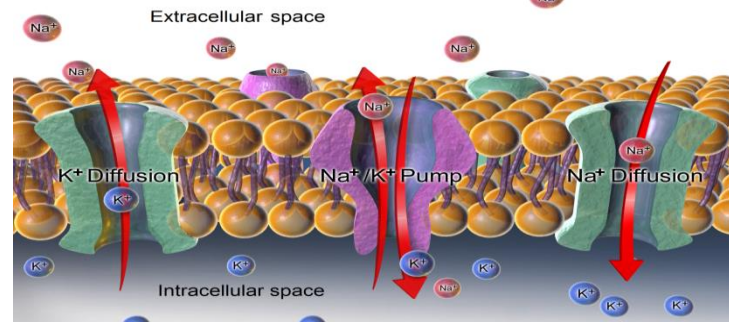
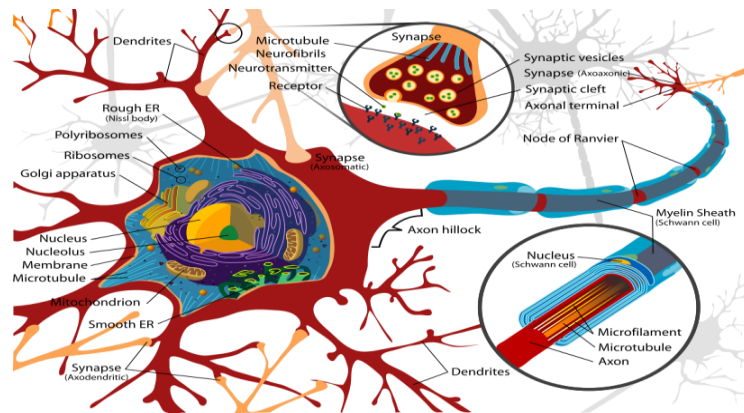
$$V = \frac{1}{C} \int idt$$



Capacitance Resistance

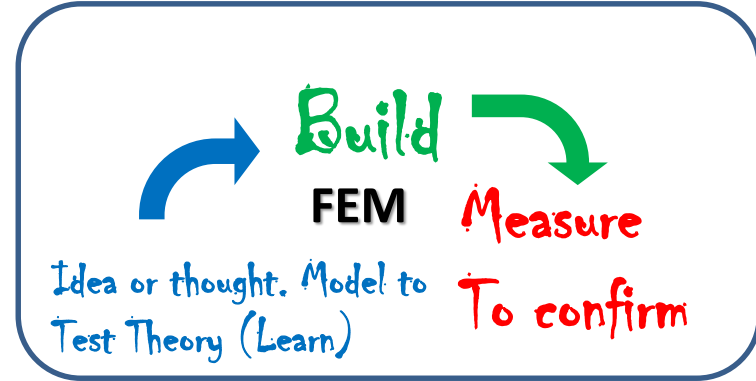
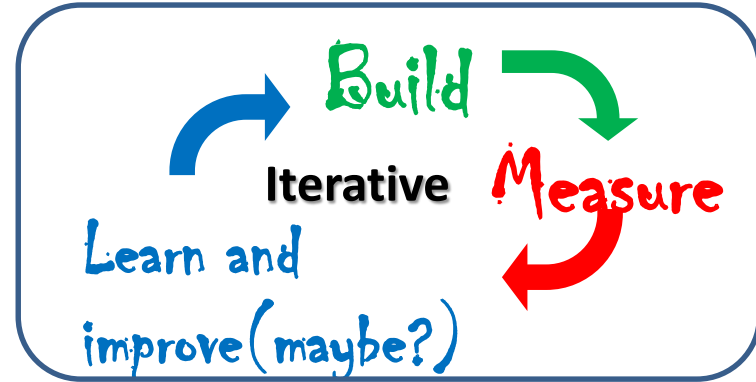
I_m : Membrane resistance
 I_1 : Longitudinal resistance
 C_m : Capacitance due to electrostatic forces

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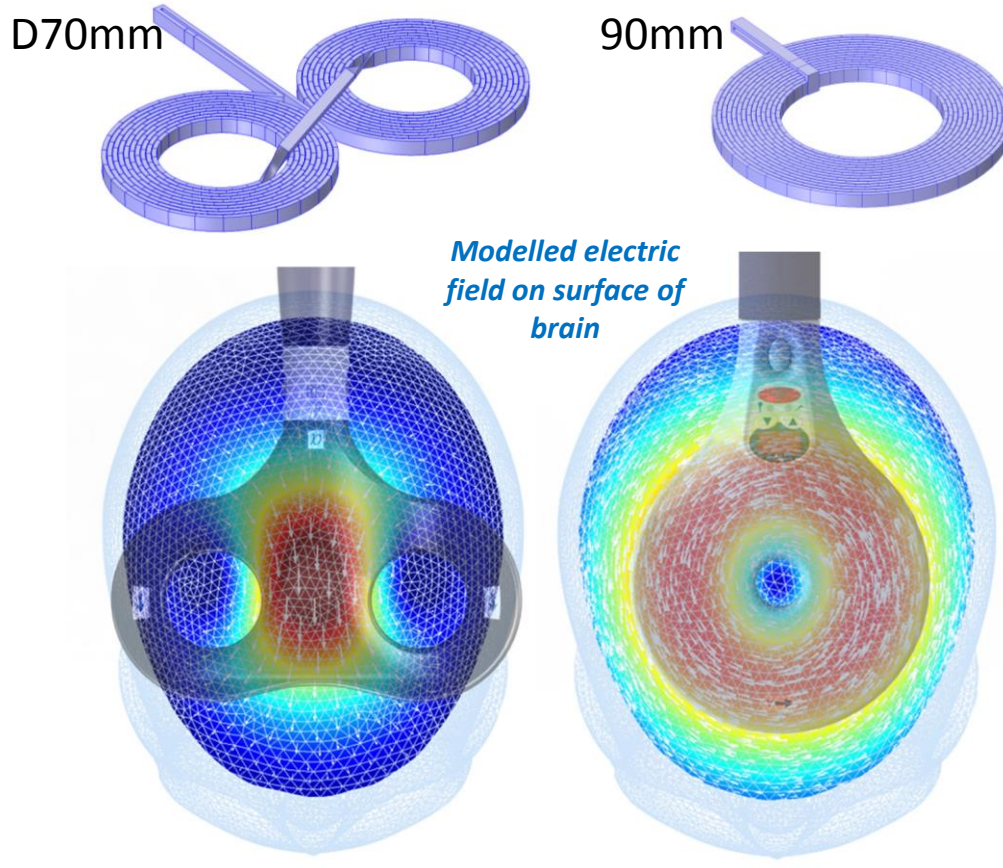
Why Does Magstim Use Finite Element Modelling?

TIME!



Most Common Coil Geometries

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➤ The Single 90mm coil is made from a single coil winding having multiple turns

➤ These coils have a broad field pattern and are used for many applications including stimulating both sides of the brain simultaneously.

➤ The D70mm coil is made from a two windings placed side by side.

➤ Where the coils touch the magnetic field distributions overlap and produce an intensity magnetic field (termed “focal”)

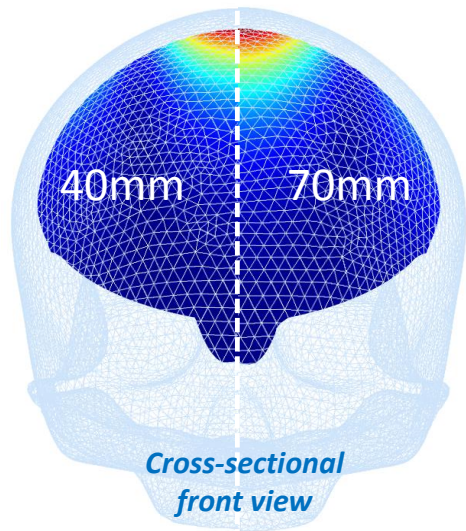
Depth-Focality Trade-off

40mm

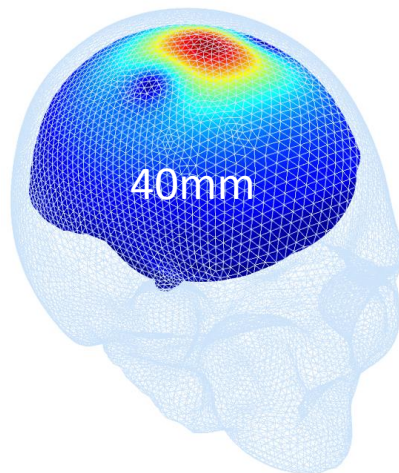
50mm

60mm

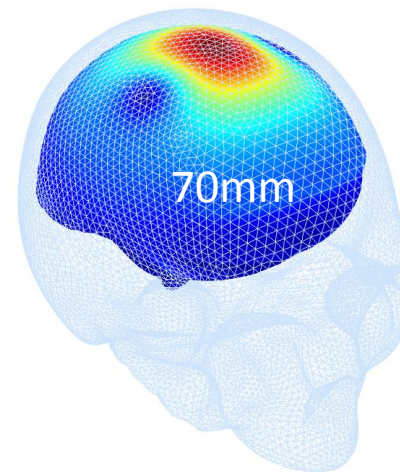
70mm



Modelled electric field on surface of brain, normalised by the pulse frequency



40mm



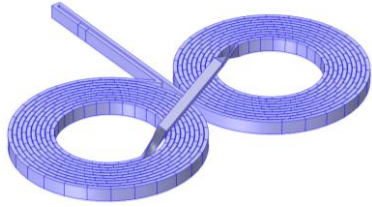
70mm

High

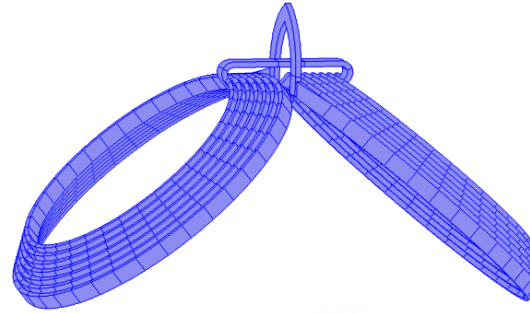


Low

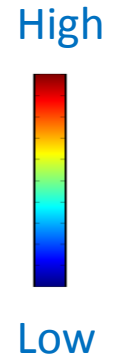
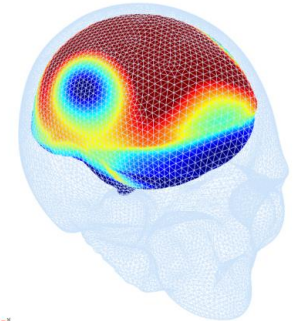
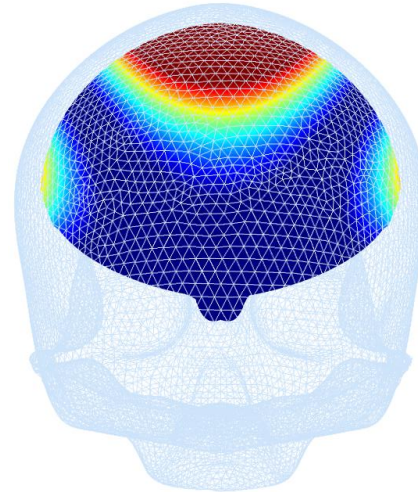
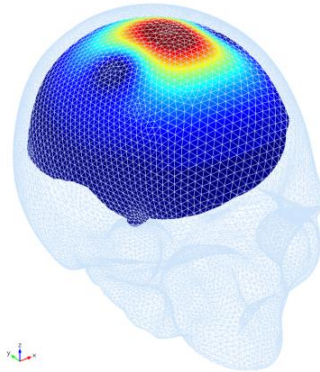
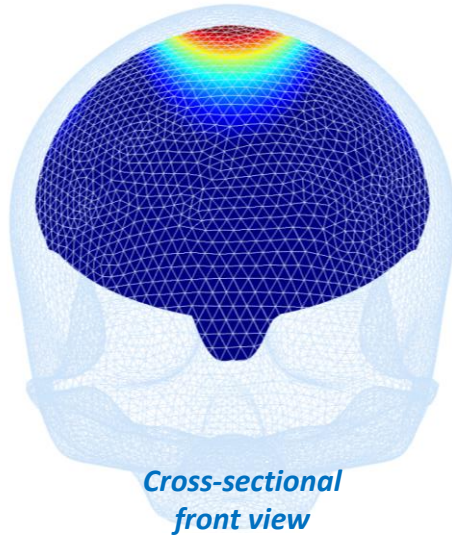
Angled coils



Angled coils
provide better
coupling to the
head



*Modelled electric
field on surface of
brain*



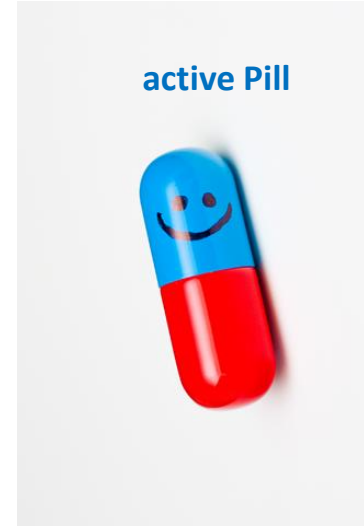
Modelling Example – Placebo Coil

- In clinical trials to assess efficacy, a control study group is required
- The control group will be given a pill with no active ingredient, whereas the test group will be given the active ingredient
- rTMS is a treatment, so how is efficacy established?
- The same way. We have to remove the active ingredient (stimulation).

Placebo Pill
(sugar pill)



active Pill



Ideal Placebo Coil Requirements

**SAME
NOISE**

SAME APPEARANCE

NO CORTICAL STIMULATION

SAME HEATING

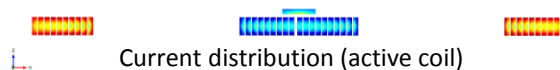
**SAME
WEIGHT**

**SOME PHERIPHERAL
STIMULATION**

SAME VIBRATION

Modelling Example – Placebo Coil, How it Works

➤ In active coils the currents in each winding flow in the same direction where the two coil windings touch. This produces an intensified magnetic field.



➤ A typical approach for placebo coils is to wire the two windings such that where the windings touch, the currents oppose each other.

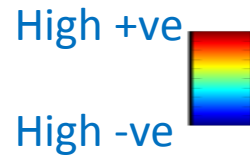
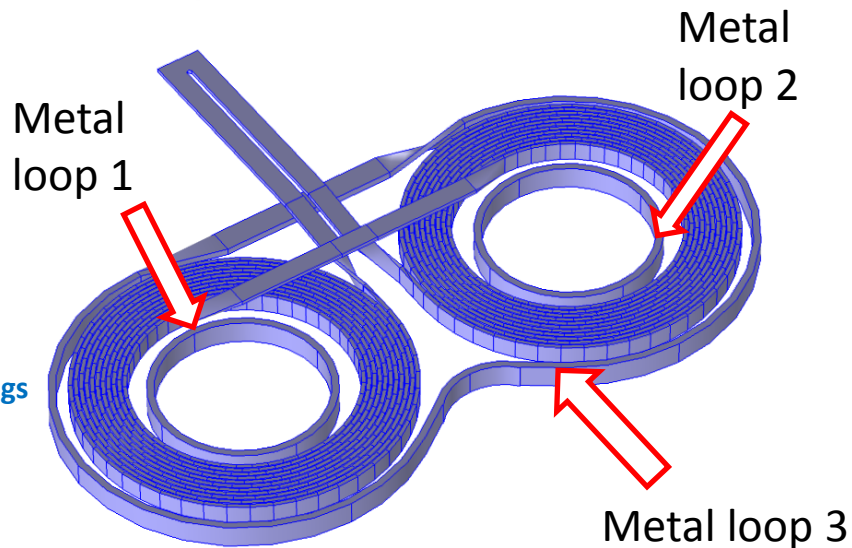
➤ This causes magnetic field cancellation but not enough to reduce the magnetic field around the coil entirely.

➤ Passive loops are placed inside the windings and a third loop around the perimeter of both windings.

➤ The induced eddy currents in these loops flow in the opposite direction to the currents in the coil which aids to further cancel the magnetic field produced from the placebo coil.



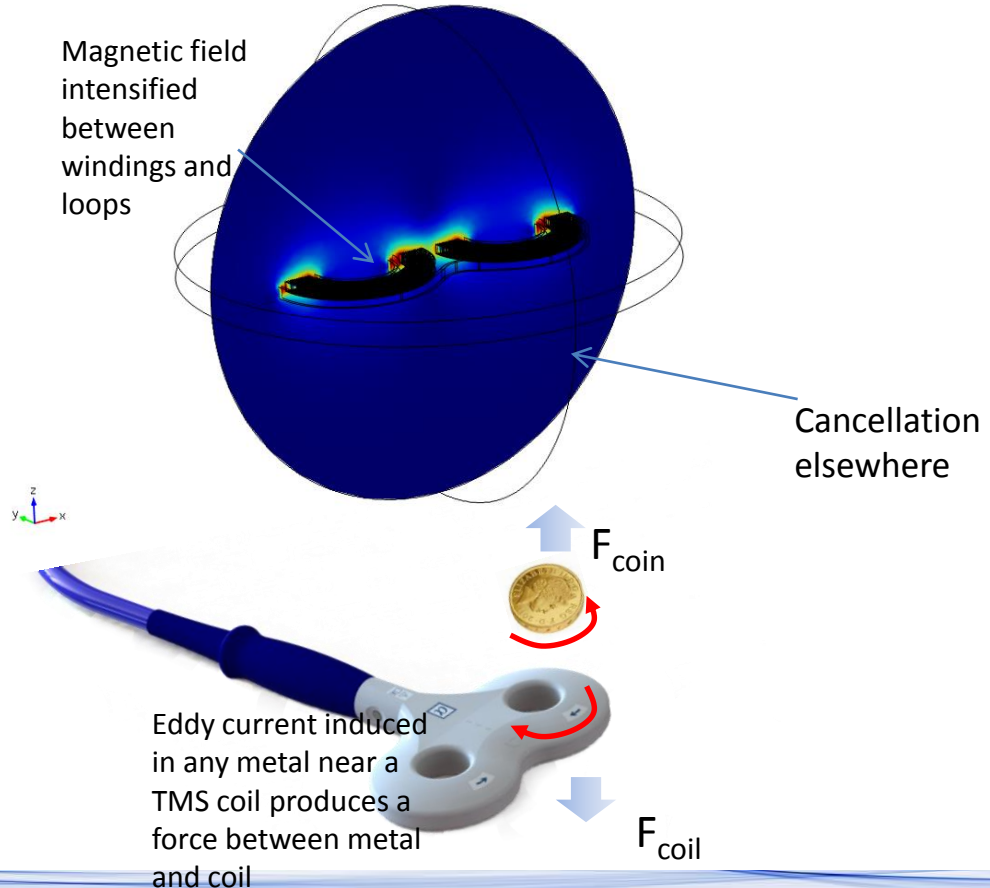
Current distribution (placebo coil)



Modelling example – Placebo Coil

How it works

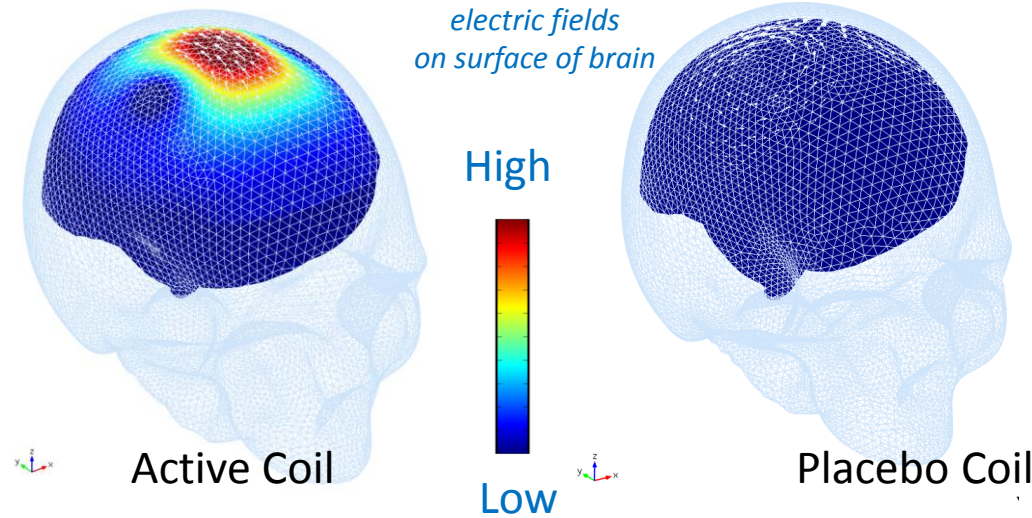
- The addition of the loops acts to cancel the field in the volume away from the coil. However it intensifies the field in the gap between the windings and loops.
- The force between coil and loop creates additional coil noise
- The coil voltage is then lowered to reduce this noise to that of the active coil.
- This further reduces the magnetic field output of the placebo coil.
- The induced current in loops is about 3 times that in coil so even at a reduced voltages the heating in the placebo coil is similar to the active coil.



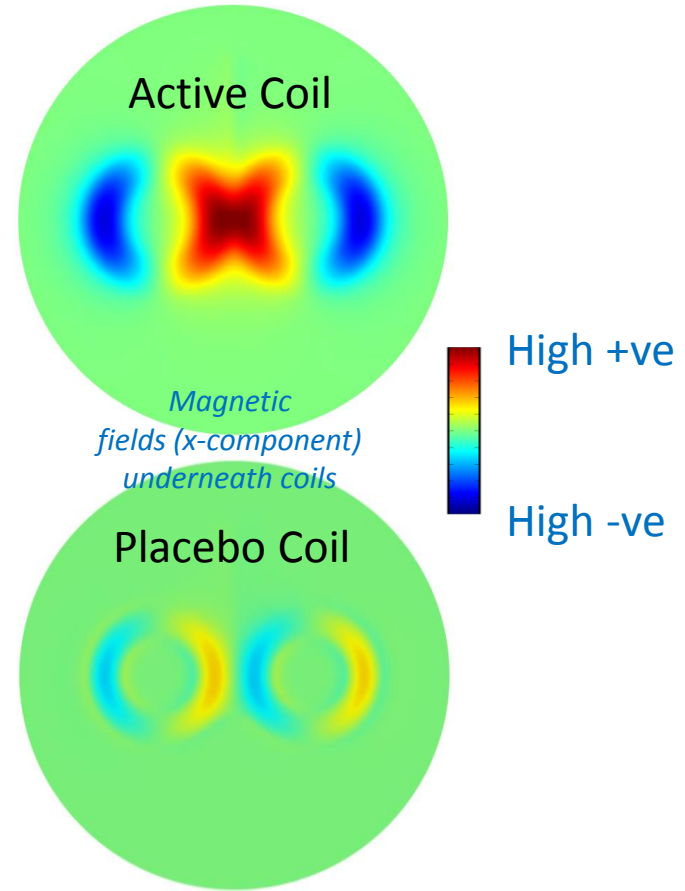
Modelling example – Placebo Coil

How it works

Result: Reduced magnetic field output, and no cortical stimulation, similar noise, similar vibration, similar heating, similar weight and same appearance as the active coil



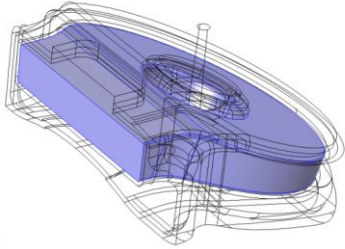
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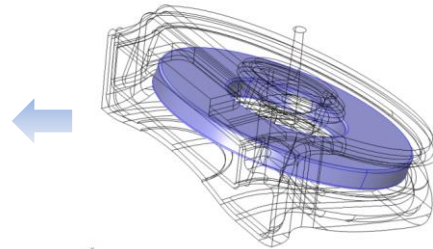
Modelling Example – Heat Transfer

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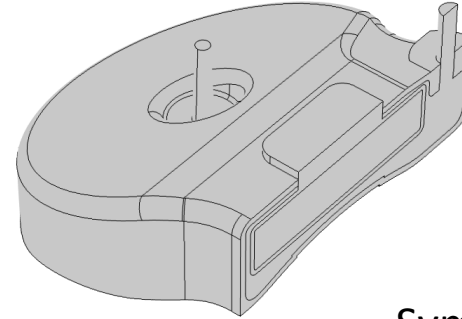
potting



Coil represented by
doughnut



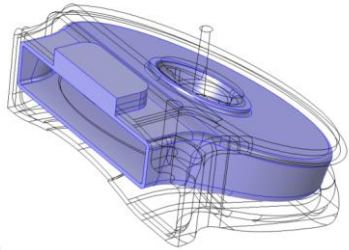
Heat transfer coil model



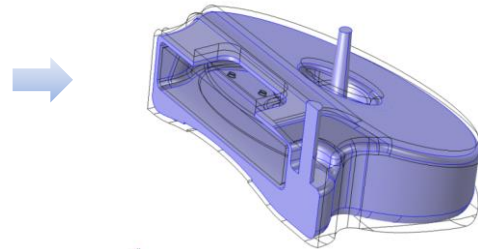
Symmetry plane



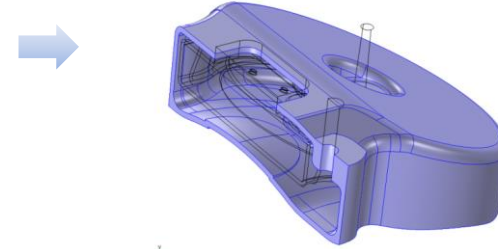
insulation



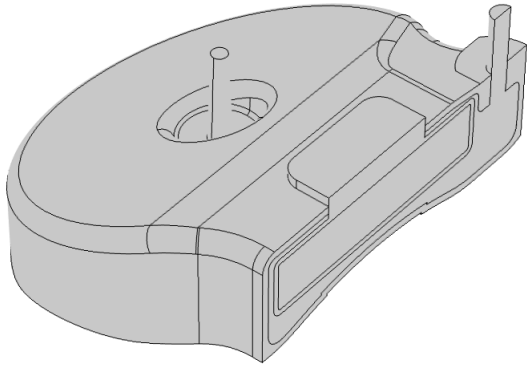
Fluid around coil



Outer casing



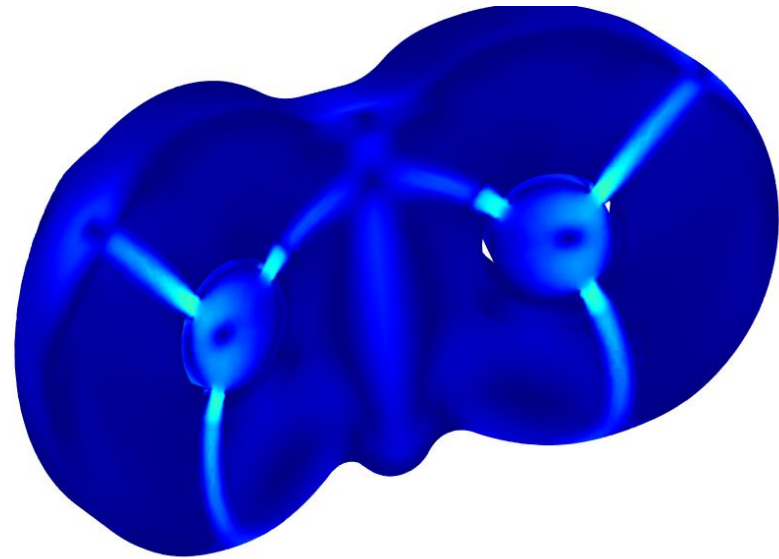
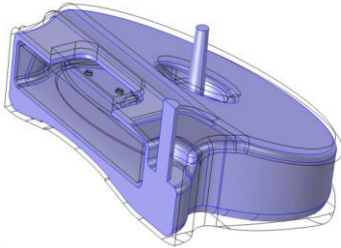
Modelling Example – Heat Transfer



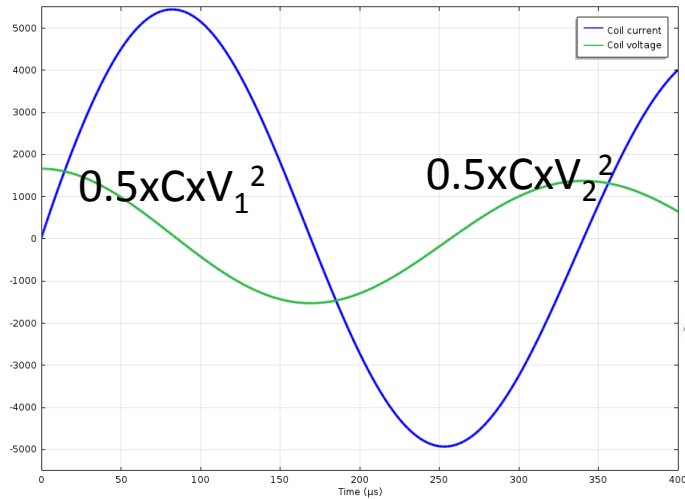
The fluid flow physics is solved using the turbulent flow physics as a steady state solution



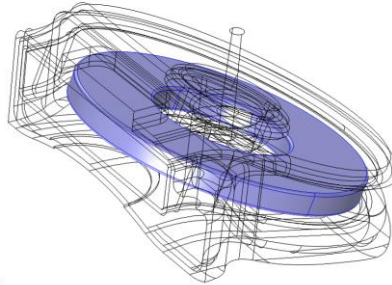
Fluid around coil



Modelling example – Heat Transfer



Heat source=300 [W]/Volume of doughnut



- Loss per pulse can be calculated from magnetic field model of coil.
- Average watts/m³ used as input to Heat transfer model
- Steady state fluid flow solution used in Heat transfer model

$$\text{Loss per shot} = 0.5 \times C \times (V_1^2 - V_2^2)$$

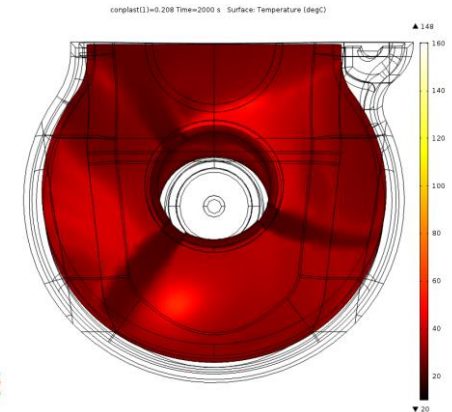
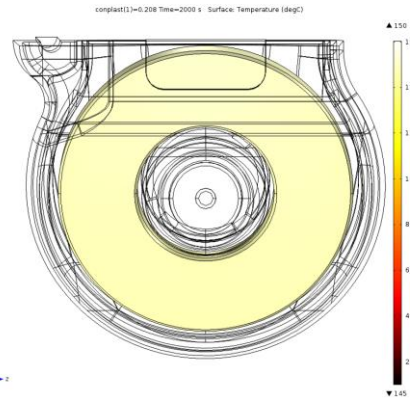
Typical Loss per shot=90[Joules]

10 shots per second (10Hz)

900[Joules per second]

5 seconds on 10 seconds off

300[Watts] average power



Modelling TMS Coil Magnetic Fields Using COMSOL – Difficulties

➤ More often than not we have to model full 3D geometries especially when modelling double coils and fields induced in the brain.

➤ Typical models require at least 40GB of RAM and it is not uncommon to nearly max out the ram on the computer (196GB)

➤ Typical spacing between windings 0.3mm, typical wire cross-section 6mmx1.75mm, typical coil size 10cmx20cm, typical air sphere size 30cm

