Magnetic Field Calculations
HV Air Heater

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2021-10-21

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Background

Background

- Electric vehicles do not have a natural heat source, such as a combustion engine, for heating the passenger cabin
- One way to produce heat for the cabin is to use an electric air heater
- Heater needs to be in the 10 kW range -> HV heater is a viable solution
- Question for concept study:
  - Will we have problem to fulfil magnetic field requirements?

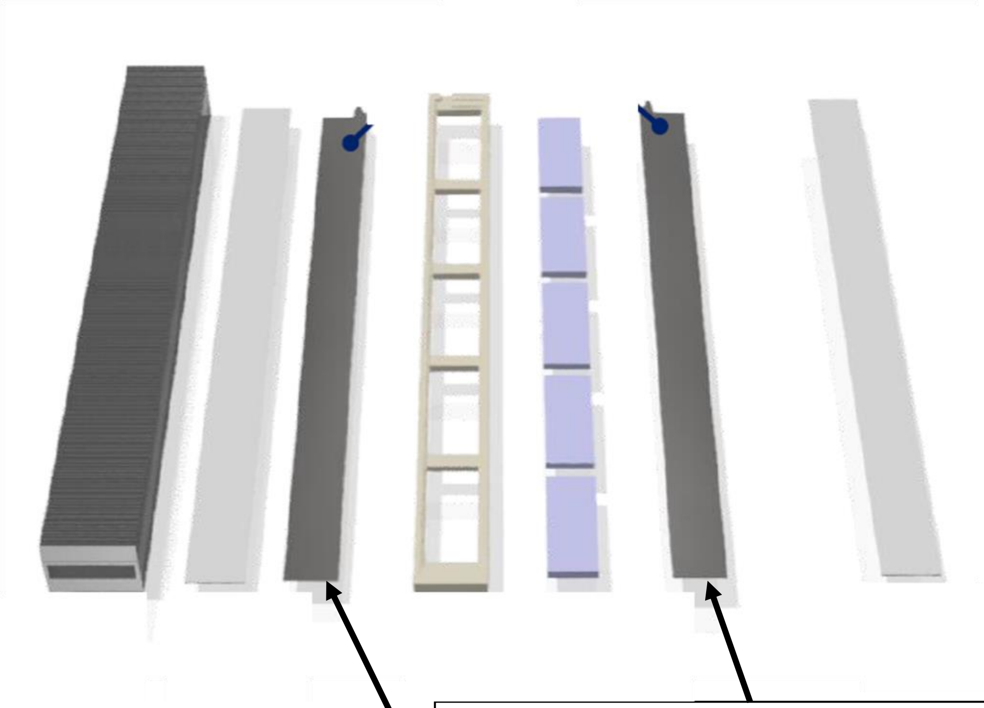
HV Air Heater

Principle of Operation

Air Heater unit

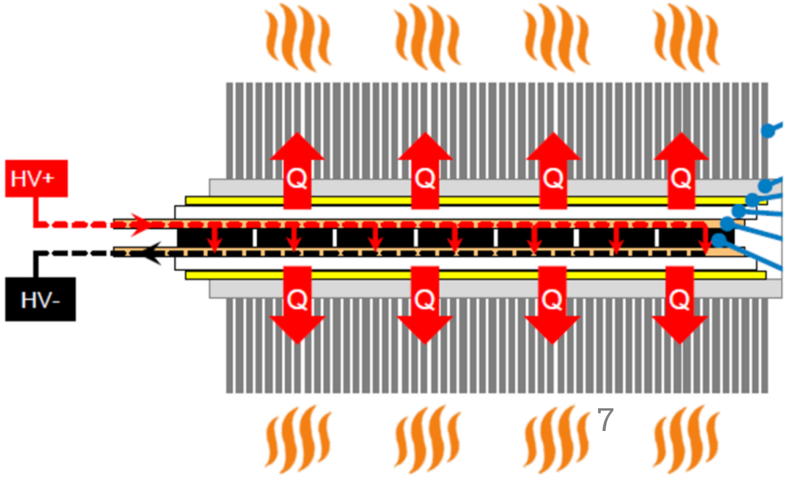
Picture shows Air Heater with 8 vertical rods of PTC stones. Nominal power 8.5 kW.

Single heater rod



Voltage applied to these two metal bars. Current will flow through the PTC stones resulting in heat.

Working principle



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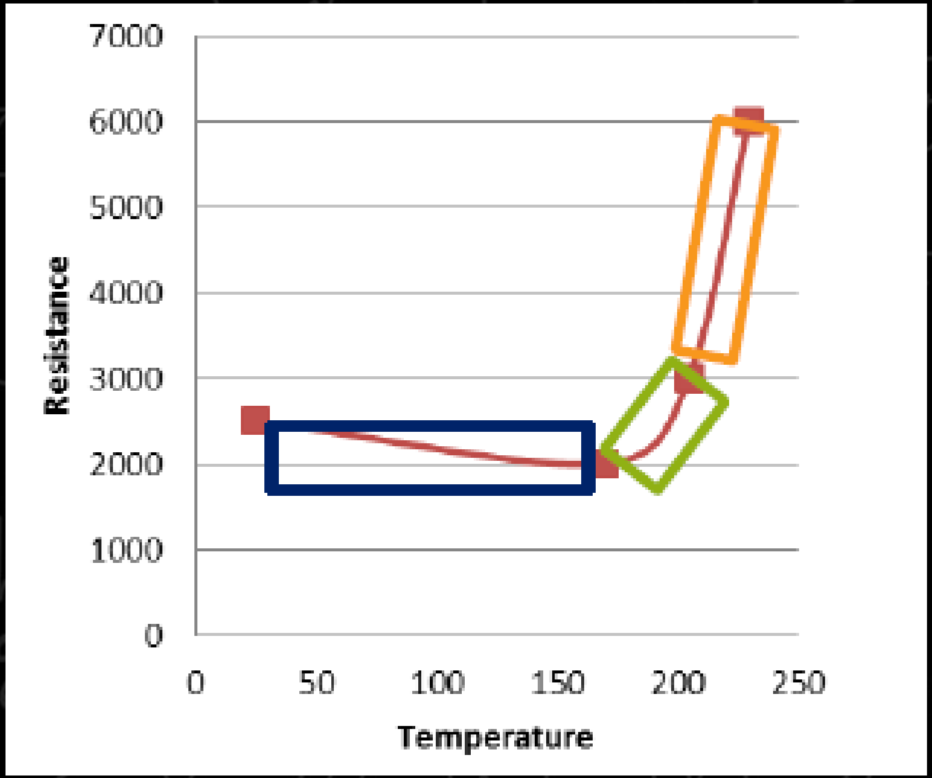
PTC Stone Characteristics

- PTC = Positive Temperature Coefficient, i.e., increased resistance with temperature
- Self-limiting temperature preventing thermal runaway



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HV Air Heater

Model for Magnetic Field Simulations

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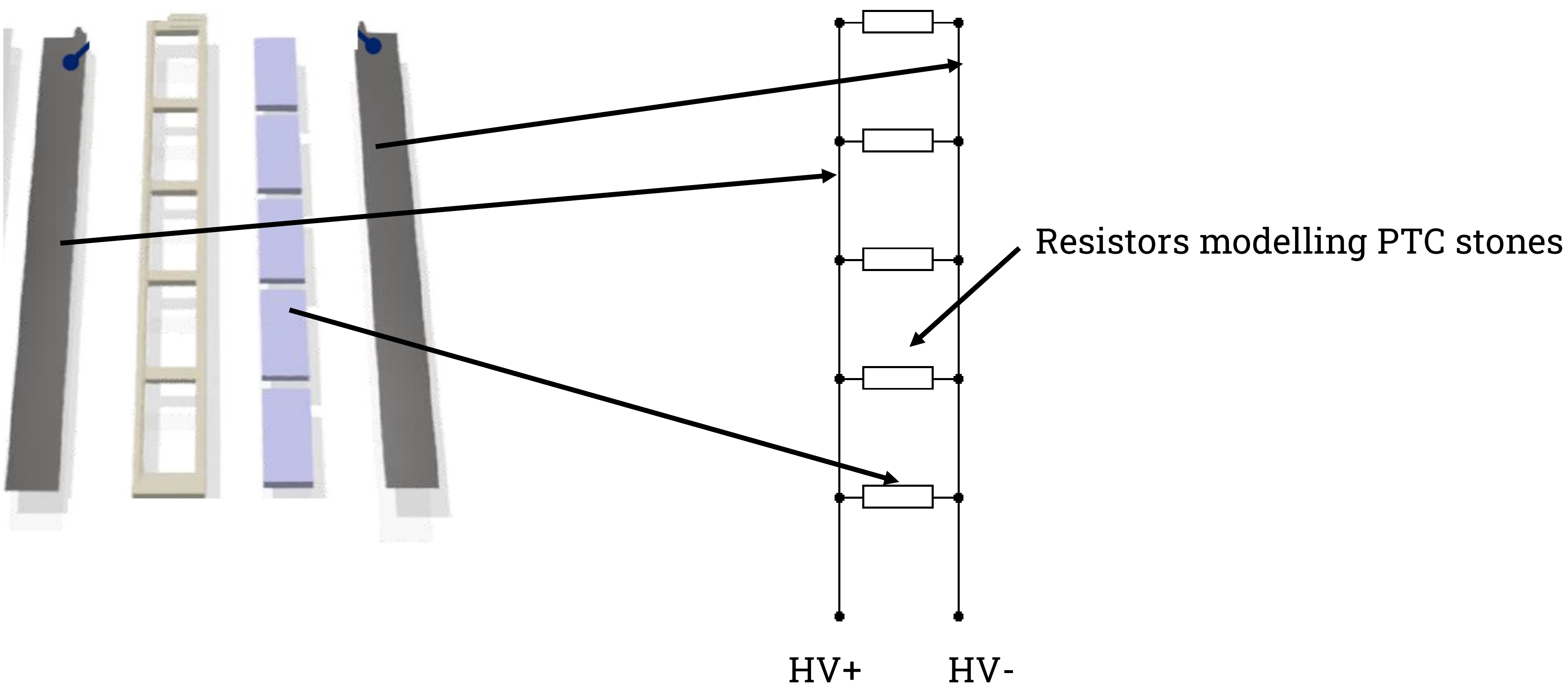
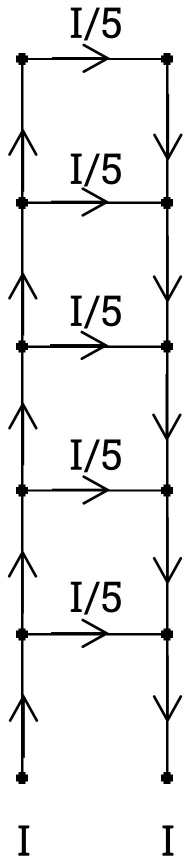
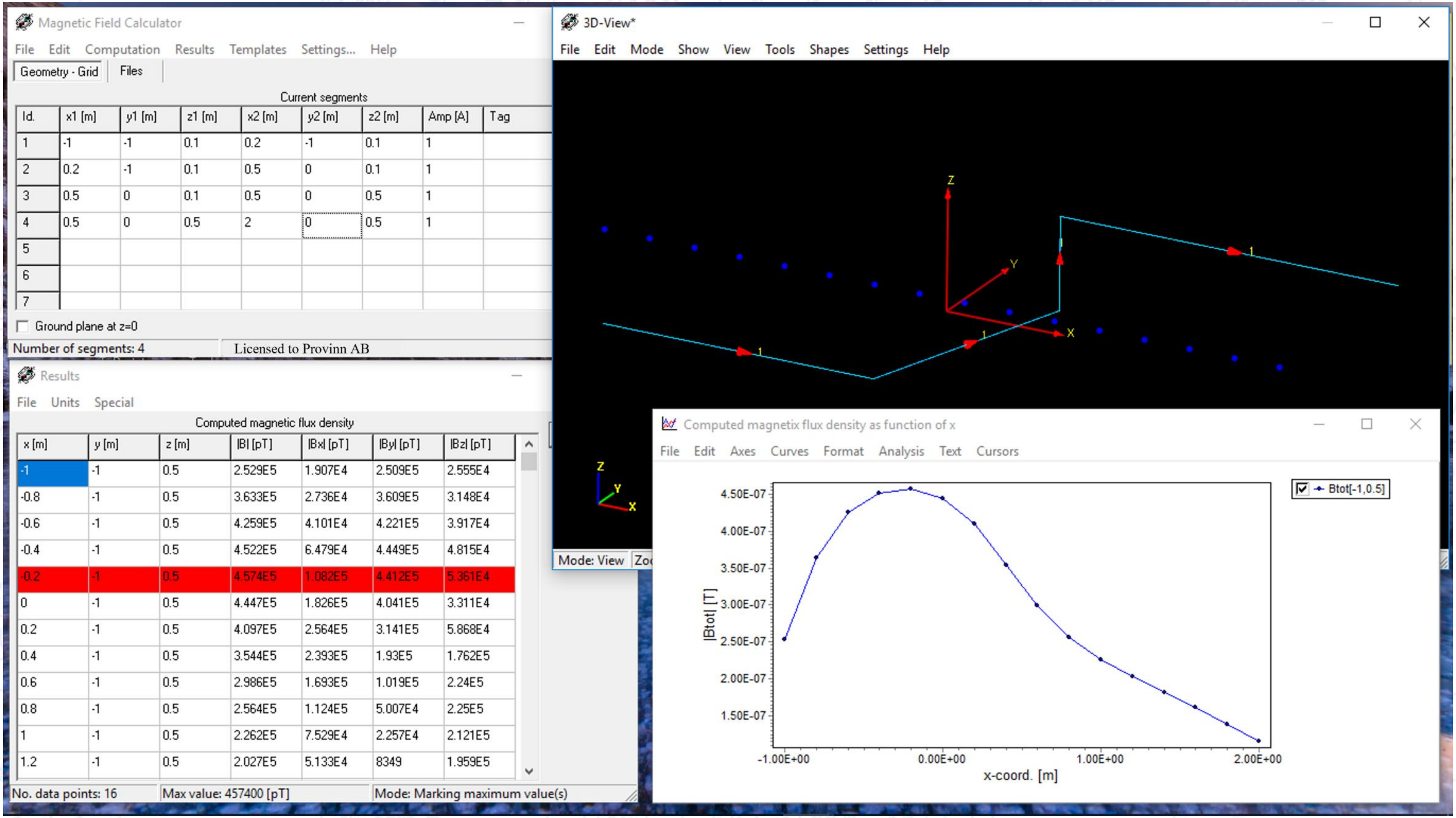
Model of heater rod



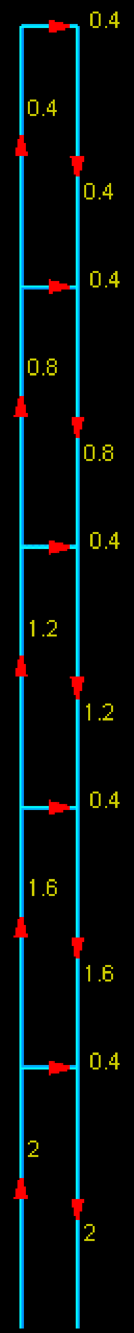




“Magnetic Field Calculator” © Jan Carlsson, Provinn AB. https://www.technologybooks.online/produkt/magnetic-field-calculator/

Model of heater rod

Picture shows simulation model of a single heater rod in the "Magnetic Field Calculator"*. Here, a feed current with an amplitude of 2A is assumed, i.e., 0.4A through each PTC stone.



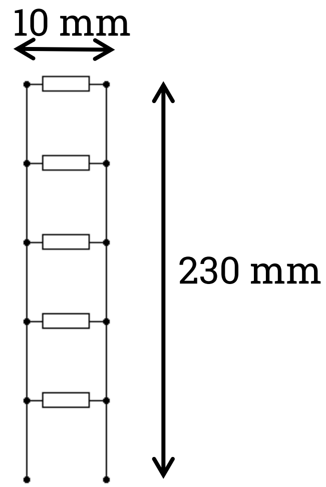
*"Magnetic Field Calculator" © Jan Carlsson, Provinn AB. https://www.technologybooks.online/produkt/magnetic-field-calculator/

Model of complete heater

- Input from manufacturer
  - Heater consists of 8 heater rods with 5 PTC stones each
  - Rods are connected in parallel

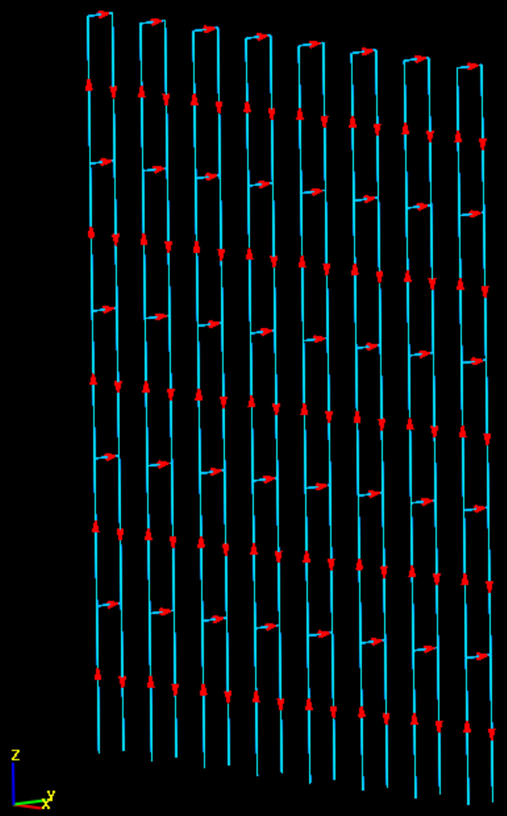
- Assumed parameters for analysis
  - A total current of 16 A, i.e., 2 A per rod
  - The distance between metal plates (i.e., thickness of PTC stones) to be 10 mm
  - The length of rods to be 230 mm
  - The centre-to-centre distance between rods to be 25 mm (25x7<195 mm)

- Rods can be connected and arranged in different ways, we do not know how this is done
  - We need to analyse several different configurations



Model of complete heater

Configuration 1 – Parallel loops, rods fed with same current direction



Loops in yz-plane

Current directions so that magnetic fields from loops will add constructively

120 current segments

Model in “Magnetic Field Calculator” © Jan Carlsson, Provinn AB. https://www.technologybooks.online/produkt/magnetic-field-calculator/

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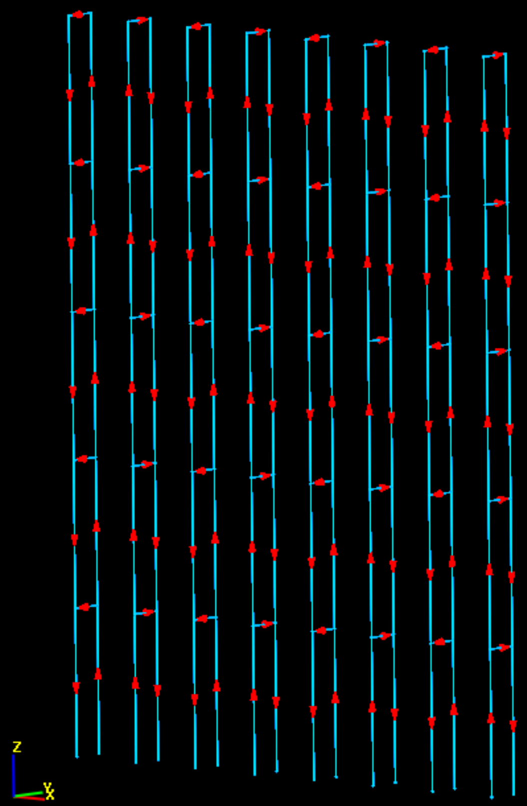
Model of complete heater

Configuration 2 – Parallel loops, rods fed with alternating current direction



Loops in yz-plane

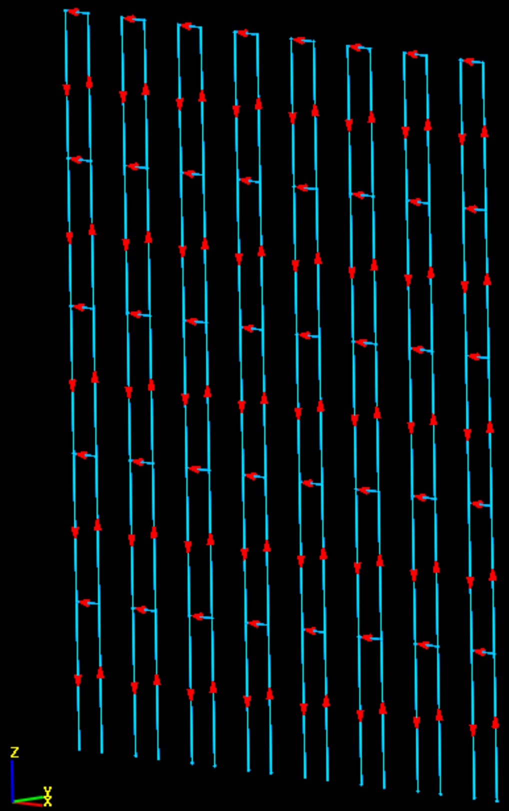
Current directions so that magnetic fields from loops will cancel

120 current segments

Model in “Magnetic Field Calculator” © Jan Carlsson, Provinn AB. https://www.technologybooks.online/produkt/magnetic-field-calculator/

Model of complete heater

Configuration 3 – Loops in same plane, rods fed with same current direction



Loops in xz-plane

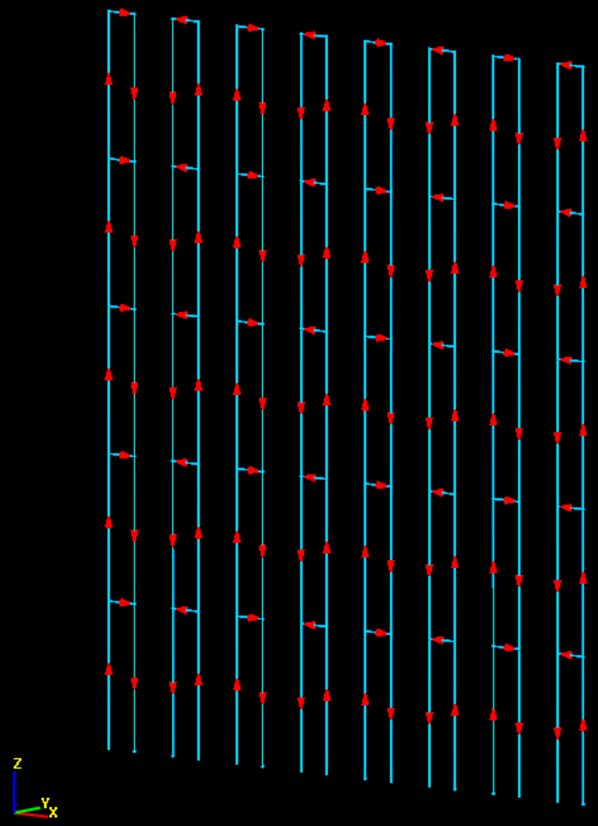
Current directions so that magnetic fields from loops will add constructively

120 current segments

Model in “Magnetic Field Calculator” © Jan Carlsson, Provinn AB. https://www.technologybooks.online/produkt/magnetic-field-calculator/

Model of complete heater

Configuration 4 – Loops in same plane, rods fed with alternating current direction



Loops in xz-plane

Current directions so that magnetic fields from loops will cancel

120 current segments

Model in “Magnetic Field Calculator” © Jan Carlsson, Provinn AB. https://www.technologybooks.online/produkt/magnetic-field-calculator/

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Analysis of complete heater

Analysis steps

1. For each configuration, compute the magnetic field in three orthogonal planes at a distance of 40 mm from heater surface
2. For each configuration, identify plane with highest magnetic field
3. Identify configurations with highest and lowest magnetic field, respectively
4. For the two identified configurations, compute magnetic field as a function of distance from heater surface. Line defined as perpendicular to heater surface and through point with maximum field in plane from Step 2

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Analysis of complete heater

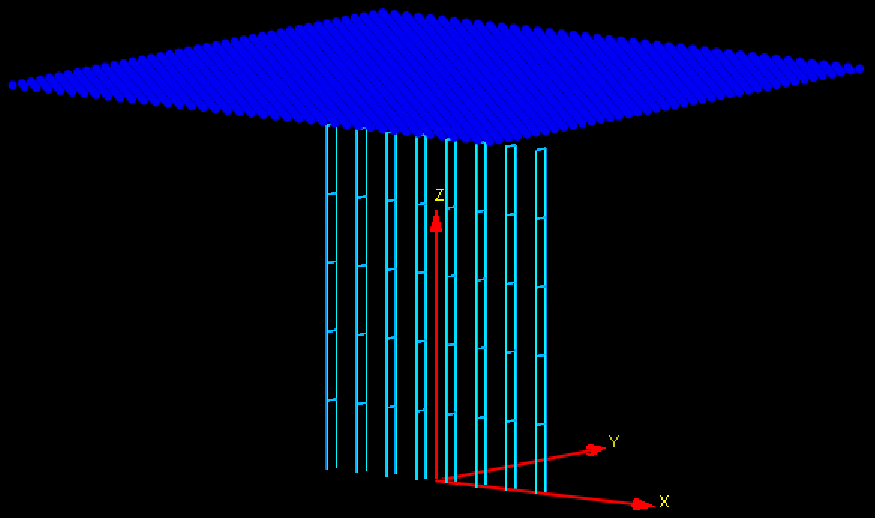
Analysis step 1a – Definition of planes (1681 field evaluation points in each plane)

xy-plane (top side)

X: [-200,200], step 10 mm

Y: [-200,200], step 10 mm

Z: 270 mm

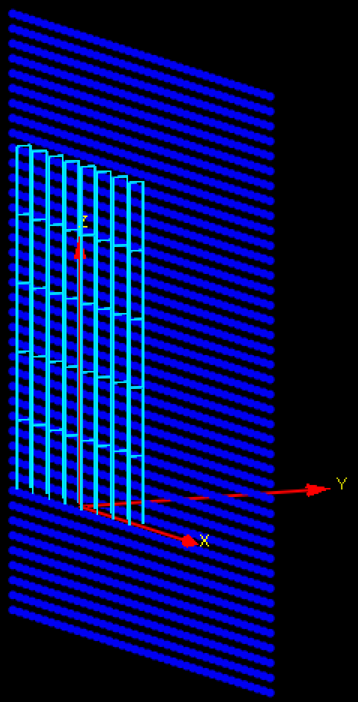


xz-plane (broad side)

X: [-200,200], step 10 mm

Y: 45 mm

Z: [-100,300], step 10 mm

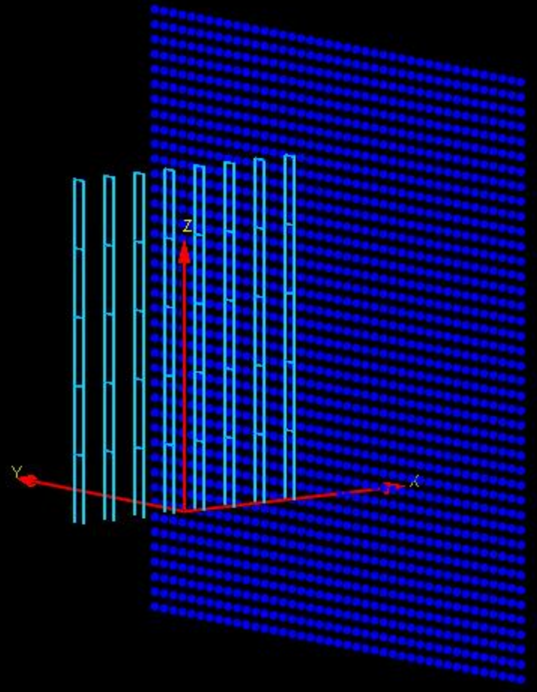


yz-plane (narrow side)

X: 127.5 mm

Y: [-200,200], step 10 mm

Z: [-100,300], step 10 mm



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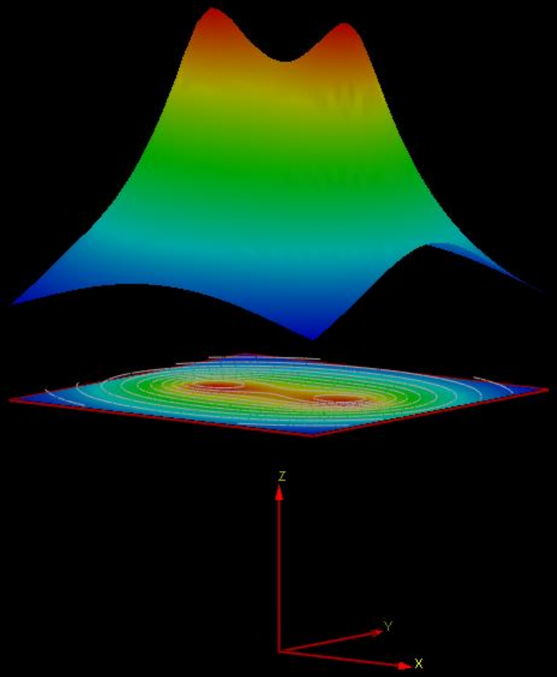
Analysis of complete heater

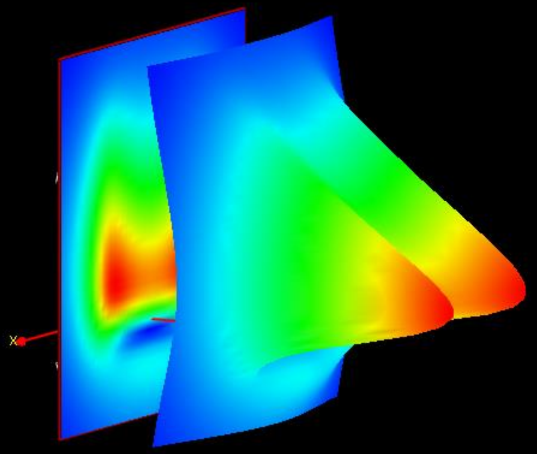
Analysis step 1b – Compute magnetic flux density (example showing Configuration 1)

<u>xy-plane (top side)</u>



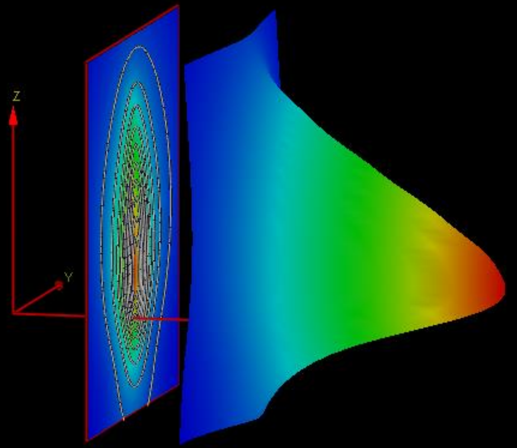
Max 0.63 µT

<u>xz-plane (broad side)</u>



Max 3.12 µT

<u>yz-plane (narrow side)</u>



Max 3.48 µT

Computed in “Magnetic Field Calculator” © Jan Carlsson, Provinn AB. https://www.technologybooks.online/produkt/magnetic-field-calculator/

Analysis of complete heater

Analysis steps 2 & 3

		Computed maximum magnetic flux density in planes [µT]		
		Plane - Top side	Plane - Broad side	Plane - Narrow side
	Configuration 1	0.63	3.12	**3.48**
Best	Configuration 2	0.13	1.29	**1.51**
Worst	Configuration 3	0.97	2.81	**3.84**
	Configuration 4	0.08	1.14	**1.78**

Observations:

1. The “best” configuration gives less than half the magnetic field as compared with the “worst”
2. As expected, alternating current feeding of rods give lower magnetic fields, reduction by a factor of more than two (compare 1&2 and 3&4, resp.)
3. Not a big difference between the two principal “loop planes” (parallel and in plane, resp.), compare 1 with 3 and 2 with 4, resp.
4. For all configurations, the maximum field is found in the plane “Narrow side”

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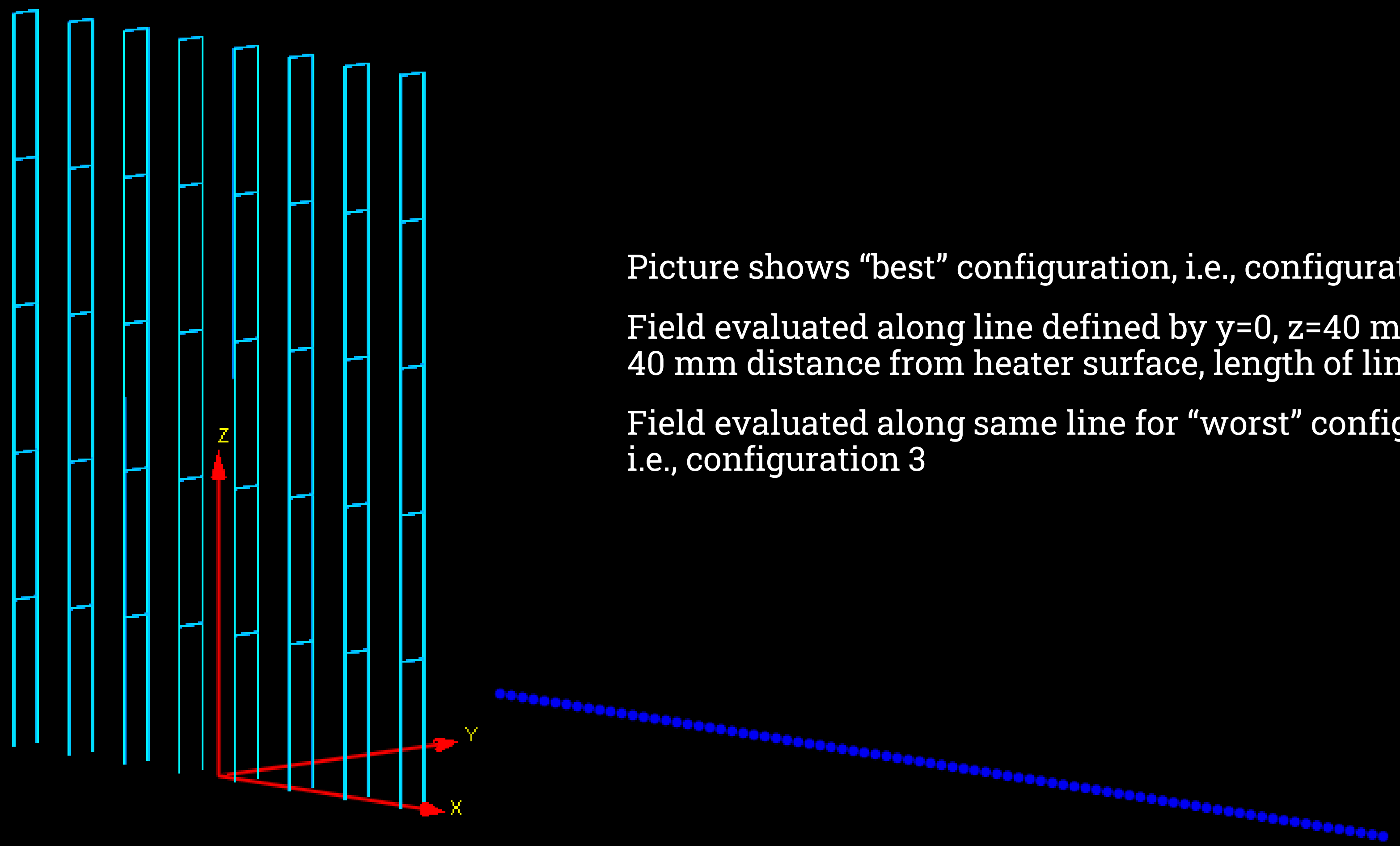
Analysis of complete heater

Analysis step 4 – Computation along line for “best” and “worst” configurations



Picture shows “best” configuration, i.e., configuration 2

Field evaluated along line defined by y=0, z=40 mm, from 40 mm distance from heater surface, length of line 400 mm

Field evaluated along same line for “worst” configuration, i.e., configuration 3

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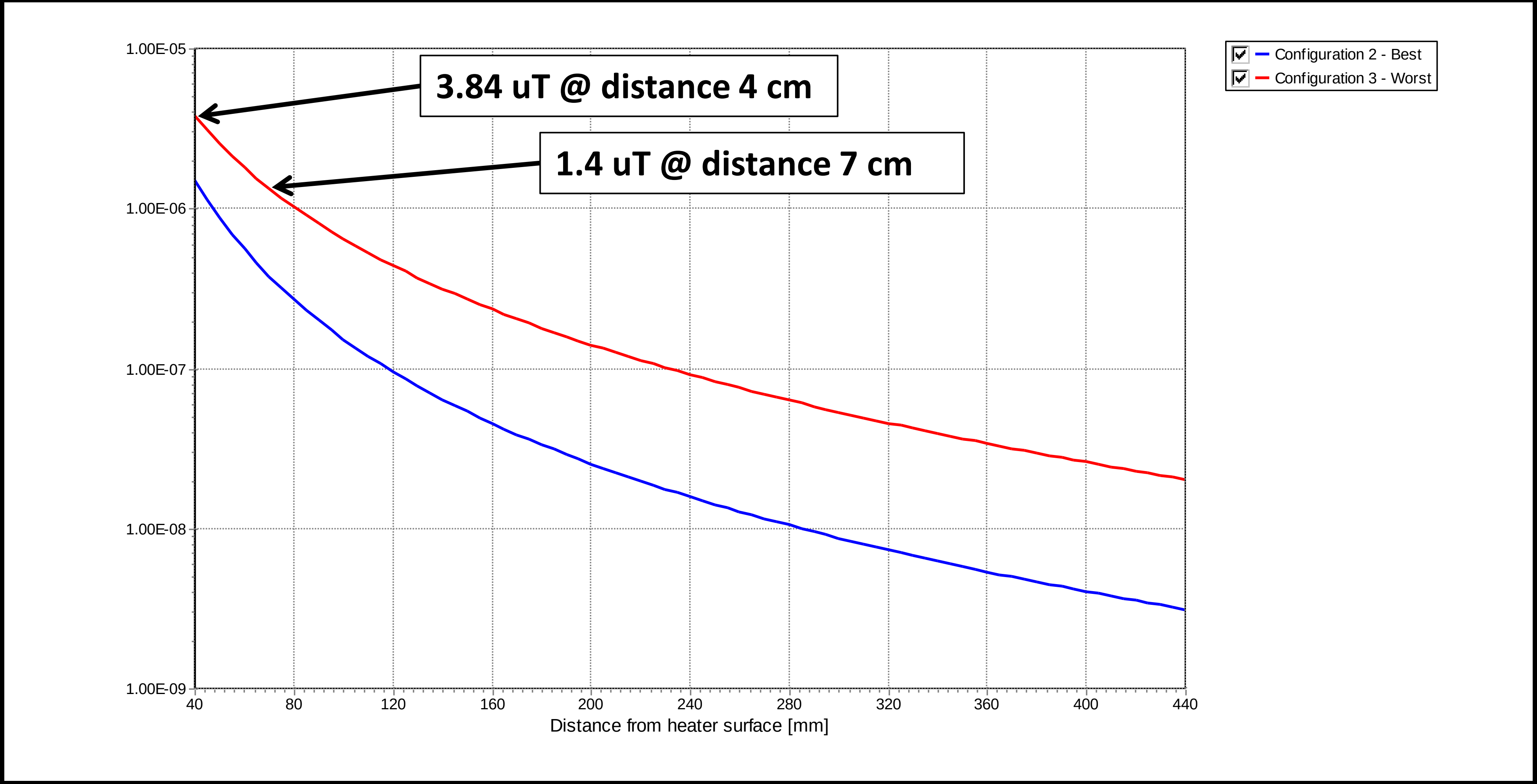
Analysis of complete heater

Analysis step 4 – Computation along line for “best” and “worst” configurations



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Magnetic Field Requirements

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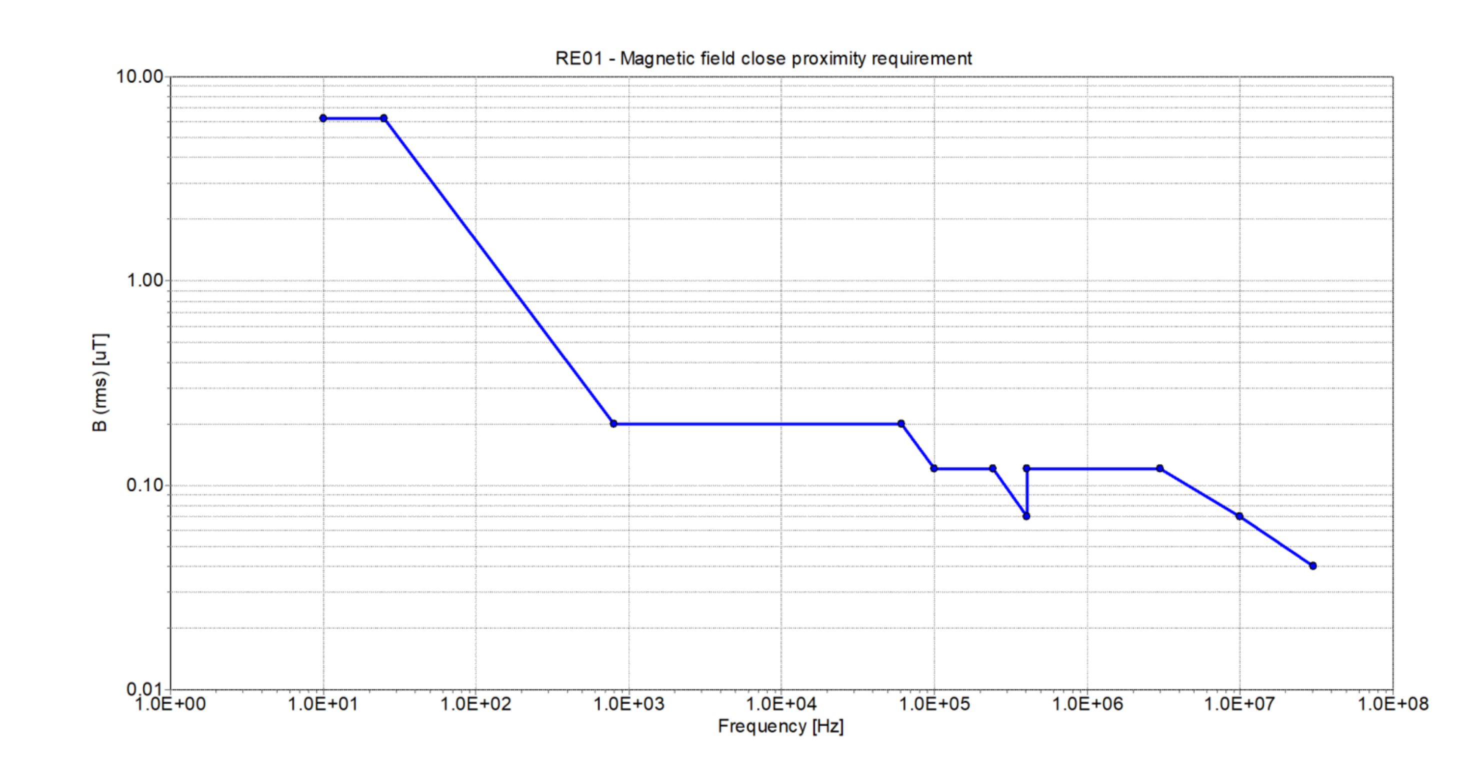
Requirement – RE01

- REO1 requirement is formulated in the frequency domain and measurements are done by using a loop at a distance of 7 cm from the surface of the equipment.
- Each frequency component (PWM) must fulfil the requirement.



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Requirement – ICNIRP

- ICNIRP limits are based on short-term, immediate effects, e.g., stimulus of muscles.

- For multi-frequency signals (PWM), a special weighting needs to be done.
  - Requirements expressed in terms of percentage value
  - Requirement is an exposure level less than 100%

- Measured in points where a person, or part off, can be located.

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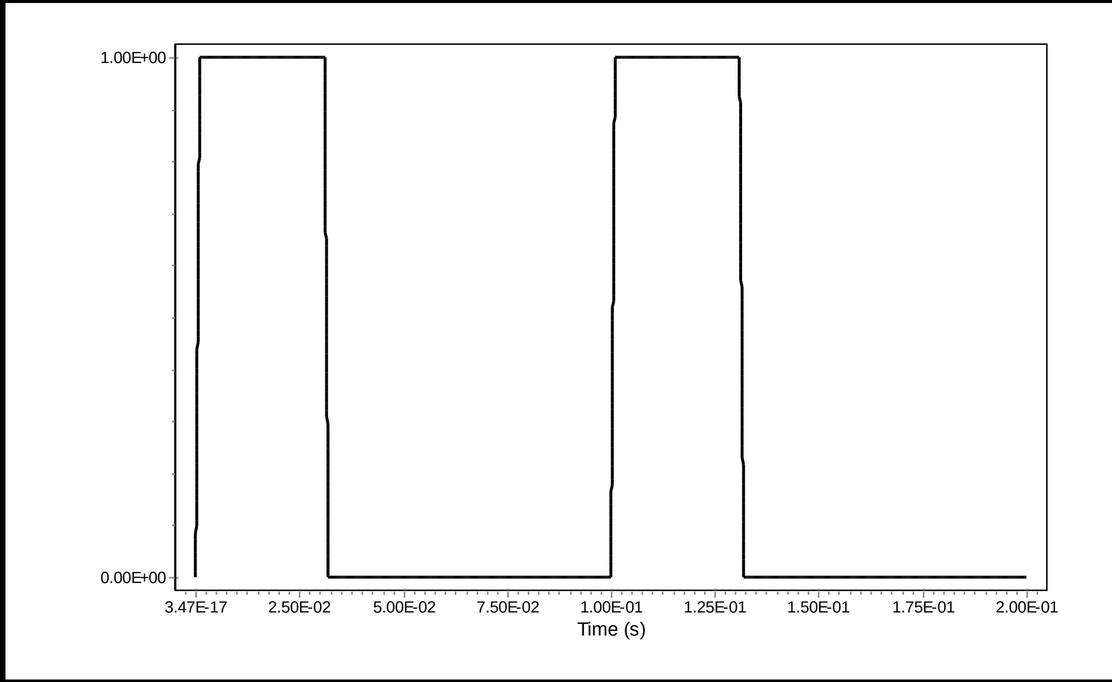
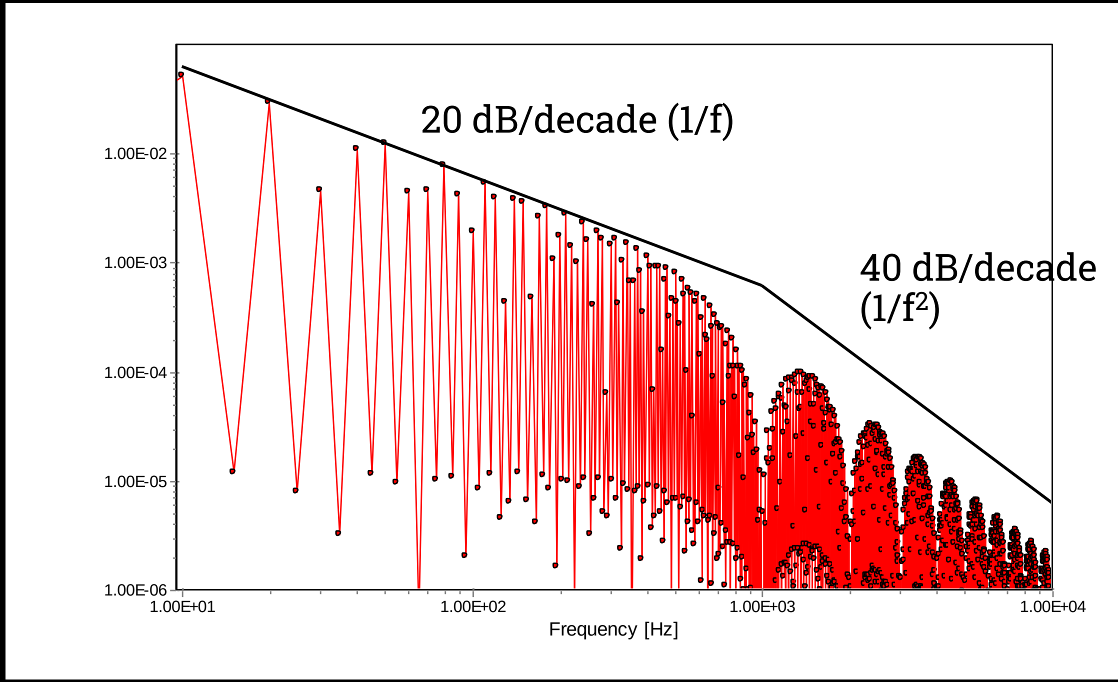
Heater Current is a PWM Signal

Simplified PWM signal – Periodic signal with constant duty cycle

Time domain – Period 100 ms, duty cycle 30%, rise/fall time 1 ms



Frequency domain – Lowest frequency 10 Hz



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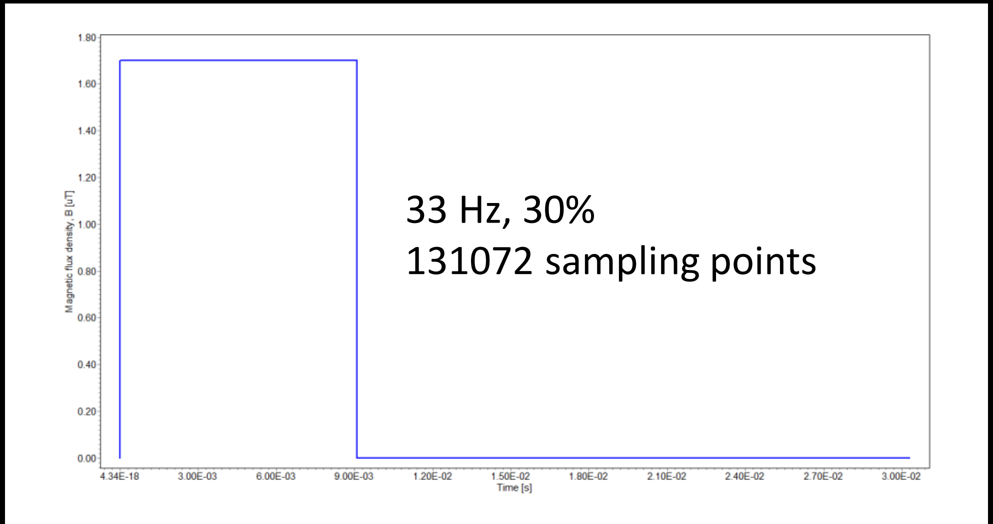
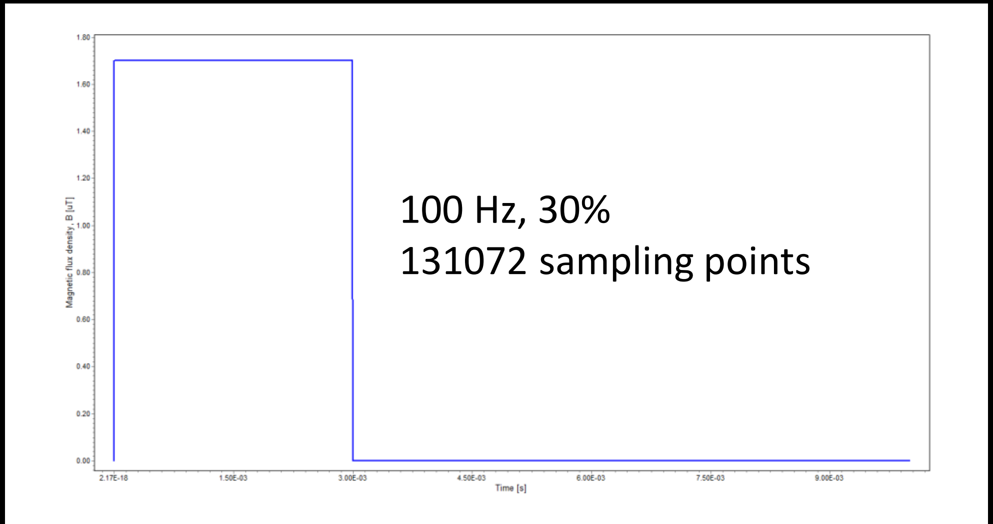
RE01 Results

RE01

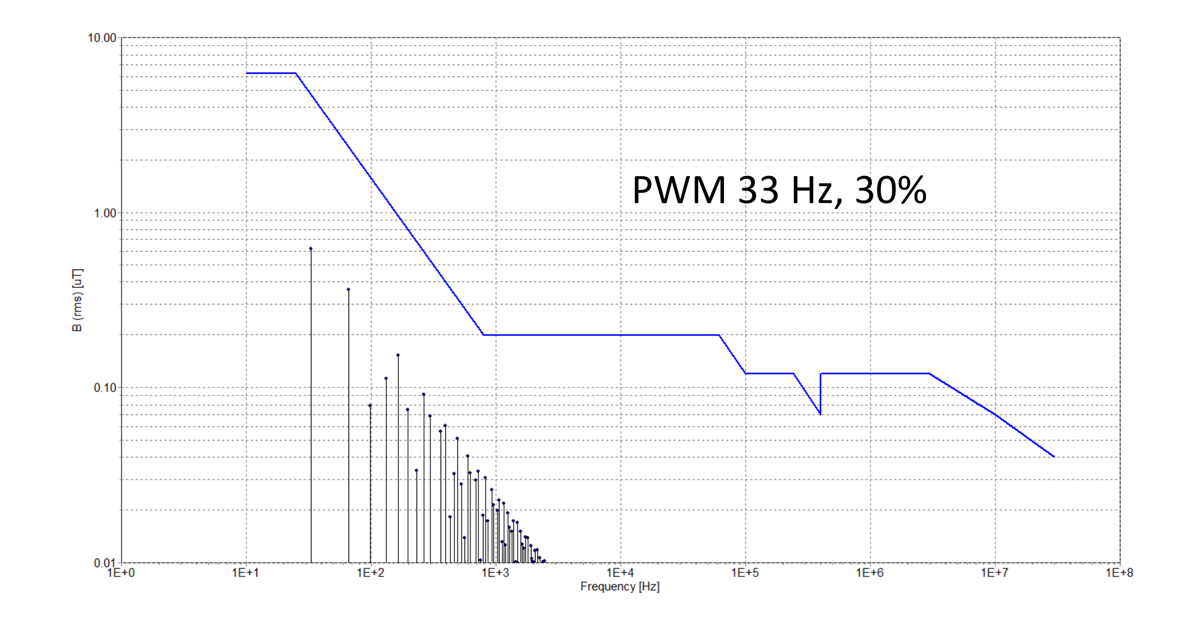
- We need to consider the frequency spectrum for the PWM signal
  - We assume the switching frequencies 33 and 100 Hz, rise/fall times of 1 µs and a duty cycle of 30%, amplitude 1.4 µT (i.e., worst case at a distance of 7 cm)
  - Time-domain plots of magnetic field at distance 7 cm:

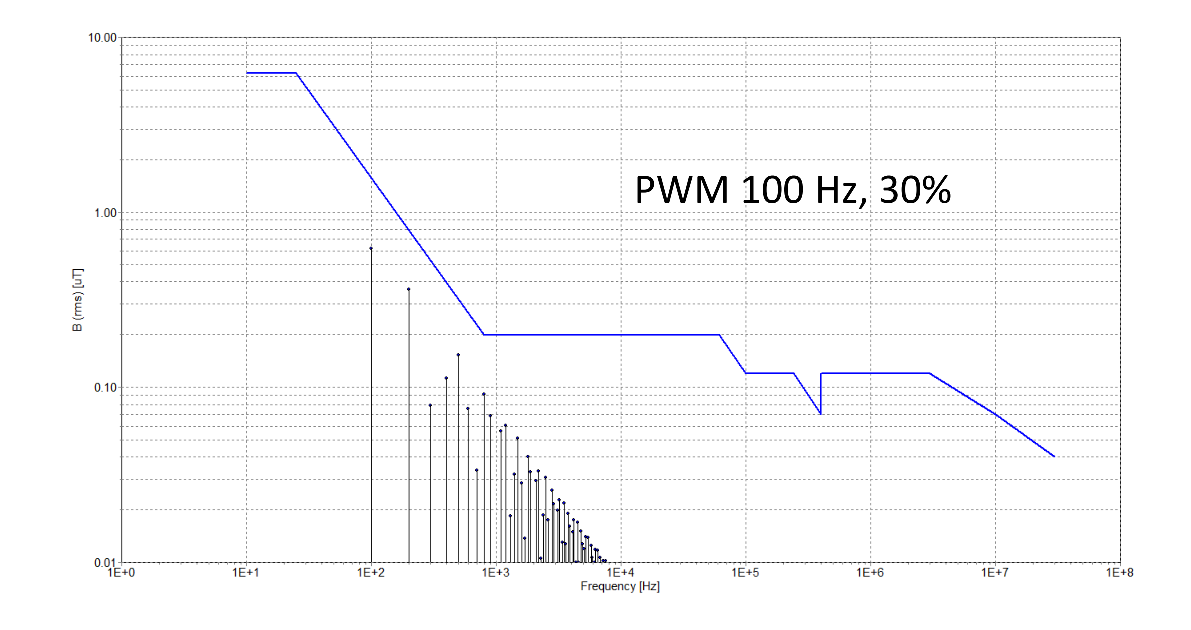




RE01

- PWM signal (magnetic field) in frequency domain, compared to RE01 limit





Conclusions – RE01

- As can be seen from the plots on the previous page, we are below the RE01 limit.

- Changing the switching frequency will have the effect of moving the spectrum to either the right (increasing switching frequency) or to the left (decreasing switching frequency). Note that the lower switching frequency the more margin to the requirement.

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ICNIRP Exposure Levels

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Calculation of ICNIRP Exposure Levels

1. Measure time domain function for magnetic flux density, B(t)
2. Transform to frequency domain to obtain B(f)
3. Multiply with ICNIRP weighting filter function to obtain m(f)=B(f)*H(f)
4. Convert weighted response, m(f), to time domain to obtain m(t)
5. Determine maximum value of m(t) to obtain m_{peak}
6. ICNIRP exposure value in percentage is finally computed as:

$$Exposure = \frac{m_{peak}}{\sqrt{2}} \cdot 100\%$$

Narda ELT-400

https://www.narda-sts.com/en/emc-products/elt-400/elt-400-2304101/

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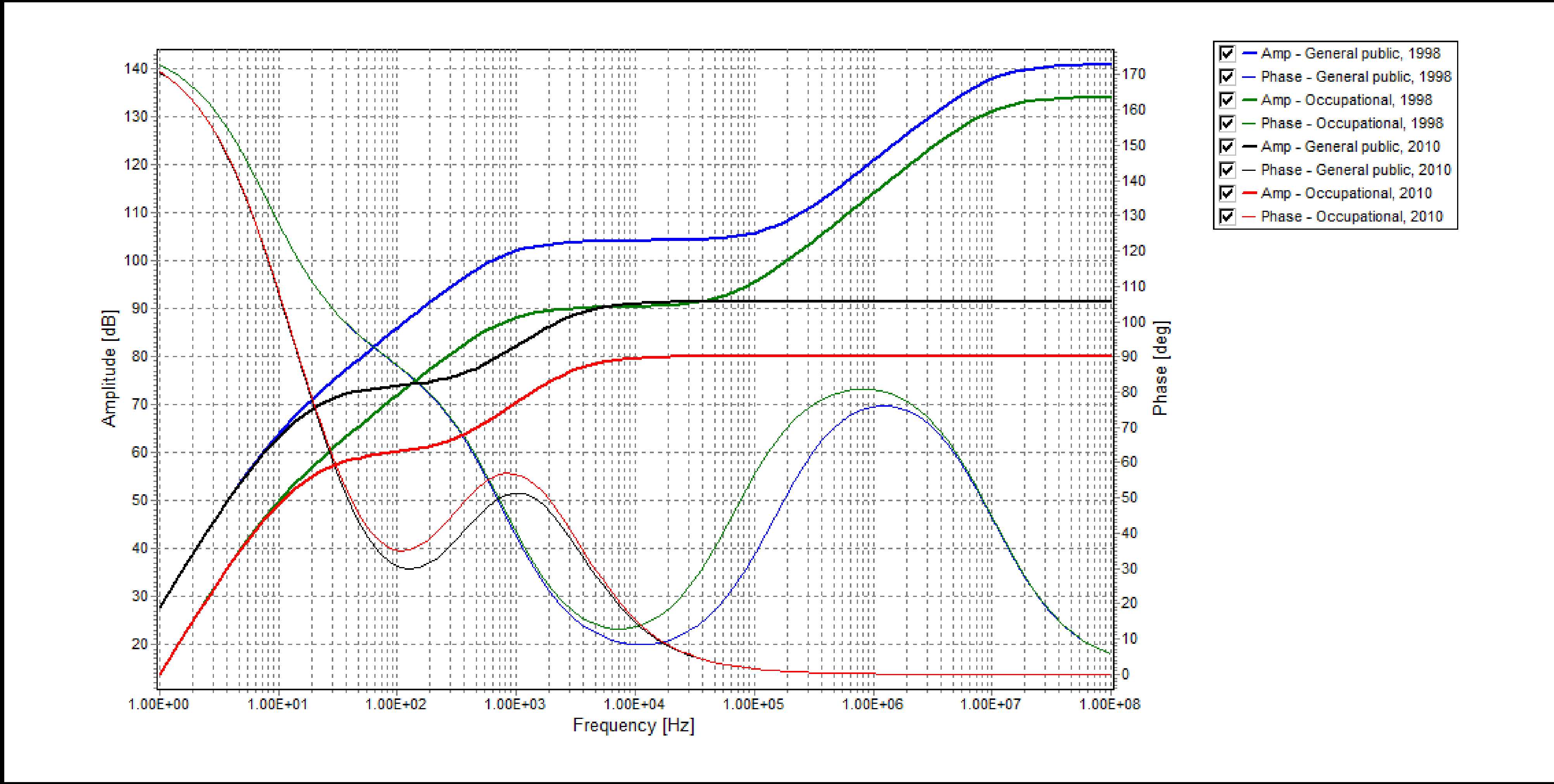
ICNIRP Weighting Filter Functions, H(f)



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Principle of Measurement Instrument

- The probe of the instrument contains three orthogonal loops that detects the three components of the magnetic field, B_x, B_y, B_z
- Each channel is bandlimited by a LP-filter with a 400 kHz cut-off frequency
- The steps explained before are executed for each channel. Before determining the exposure value, the m(t) to be used in Step 5 is calculated as:

$$m(t) = \sqrt{m_x^2(t) + m_y^2(t) + m_z^2(t)}$$

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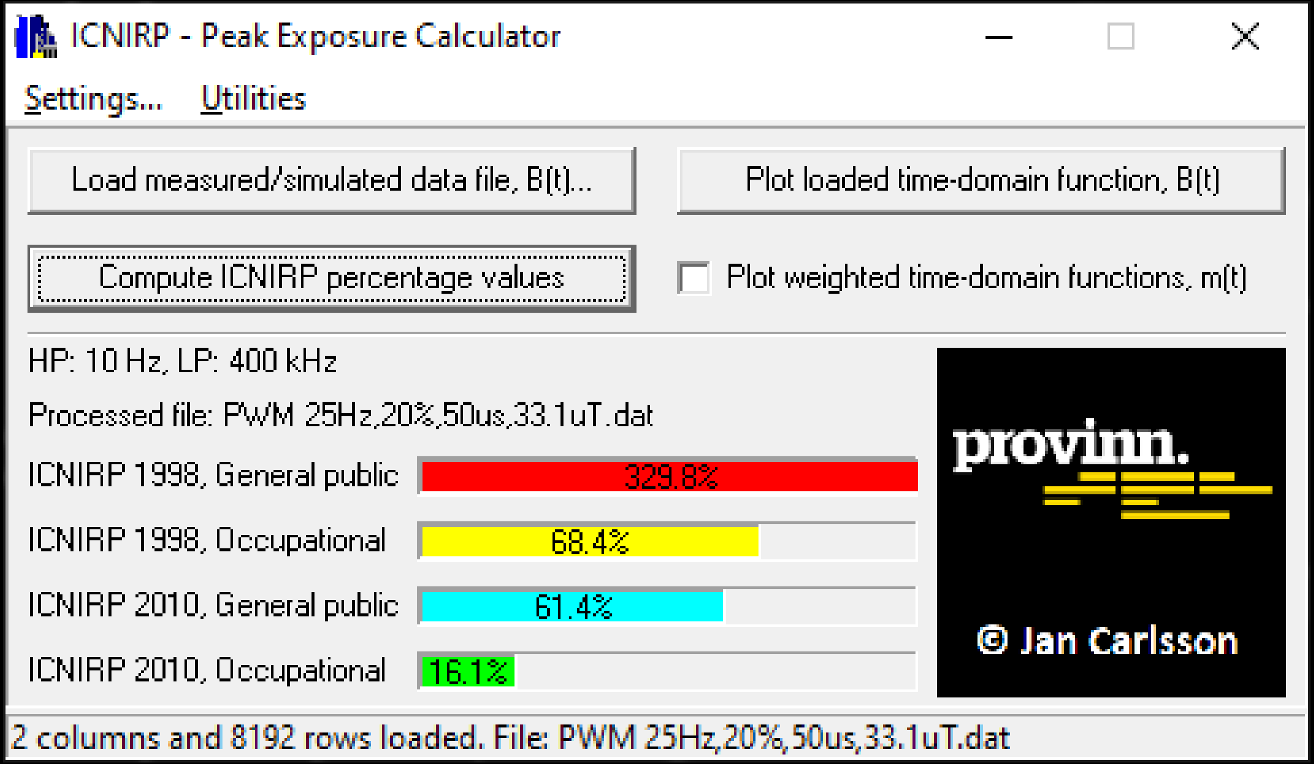
ICNIRP – Peak Exposure Calculator

To mimic the function of an ICNIRP exposure measurement instrument a computer code called “ICNIRP – Peak Exposure Calculator” has been developed. The code imports a time domain function containing either the total field as function of time, B(t), or a file containing data for each of the three field components, $B_x(t)$, $B_y(t)$, $B_z(t)$ and then computes the exposure levels as described earlier.

Exposure values computed by the code have been validated against measurements done in a Helmholtz coil. Measurements in this case were done with the instrument Narda ELT-400. Exposure levels are computed according to both ICNIRP 1998 and 2010 for general public as well as occupational.

ICNIRP – Peak Exposure Calculator



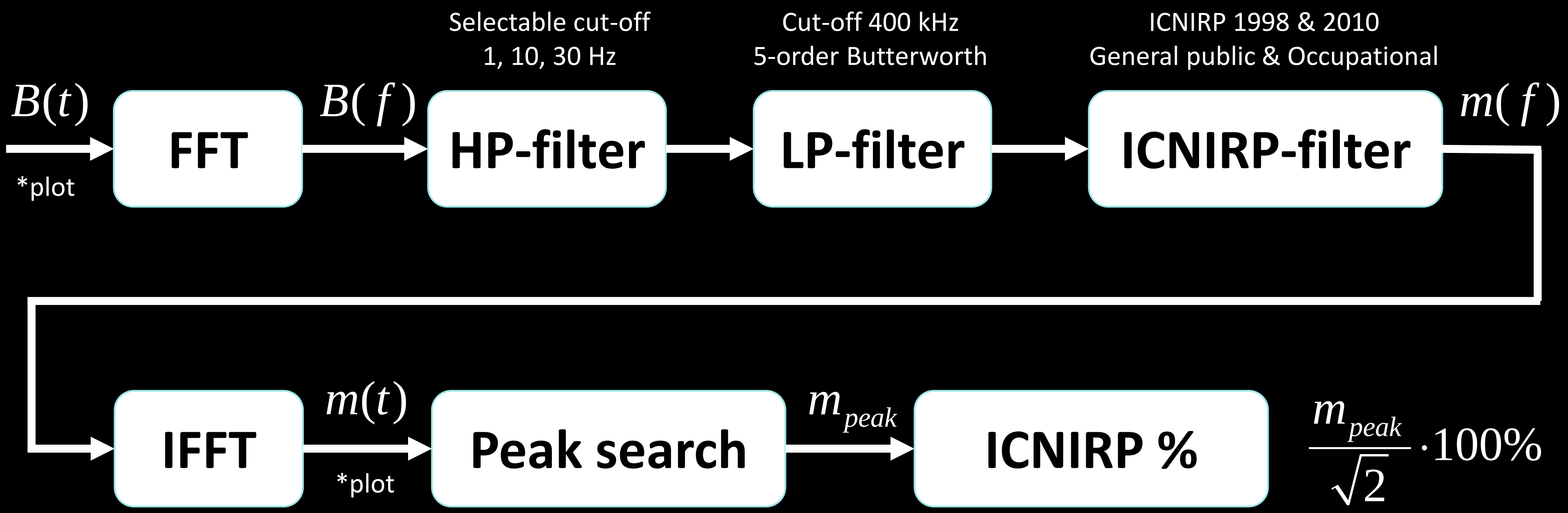
“ICNIRP - Peak Exposure Calculator” © Jan Carlsson, Provinn AB, 2021.

Narda ELT-400

https://www.narda-sts.com/en/emc-products/elt-400/elt-400-2304101/

ICNIRP filter implementation based on expressions in Narda document “The signal processing in the ELT-400”, dated 2014-05-14

ICNIRP – Peak Exposure Calculator



*option to plot in program, characteristics for HP-, LP- and ICNIRP-filters can also be plotted

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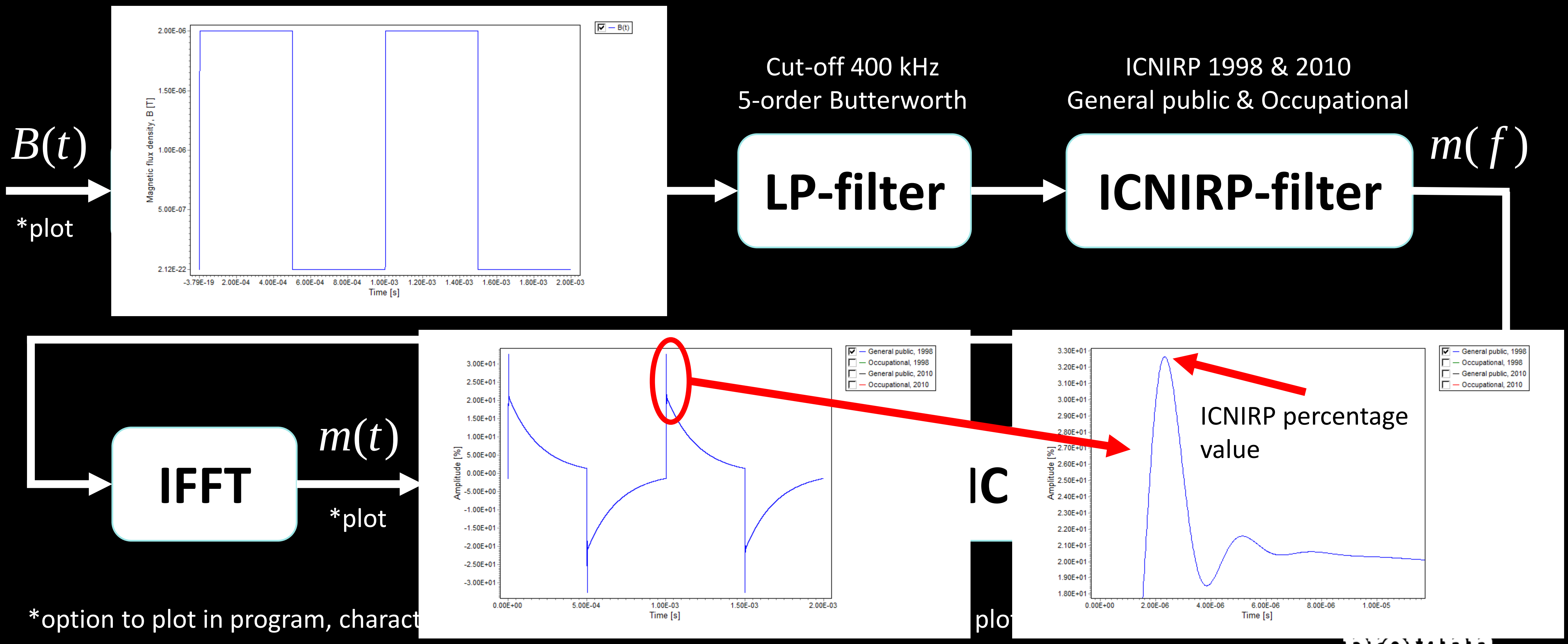
ICNIRP – Peak Exposure Calculator

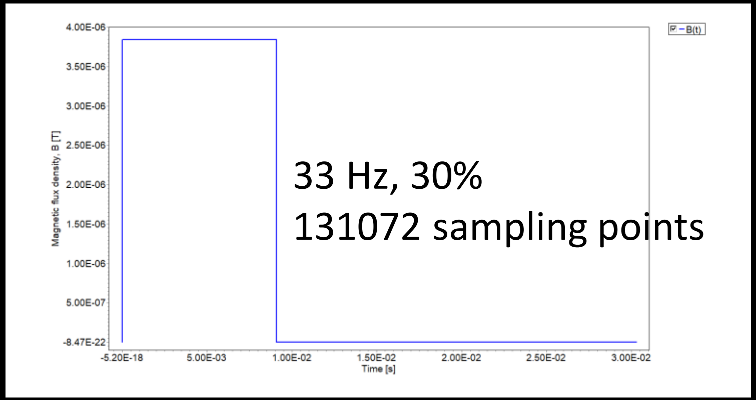


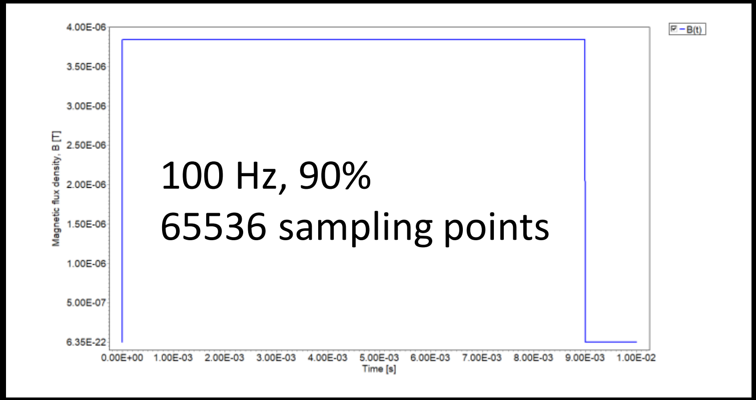
*option to plot in program, charact

ICNIRP Exposure Levels
Air Heater – Results

PWM

- Peak magnetic field 3.84 µT. Switching frequency 33 or 100 Hz. Rise time 1 µs.
- We assume a periodic PWM signal, i.e., constant duty cycle. We compute for different duty cycles.
- Note: ICNIRP General public, 1998 gives the highest exposure values, and will therefore be dimensioning -> We will in the following consider only GP 1998





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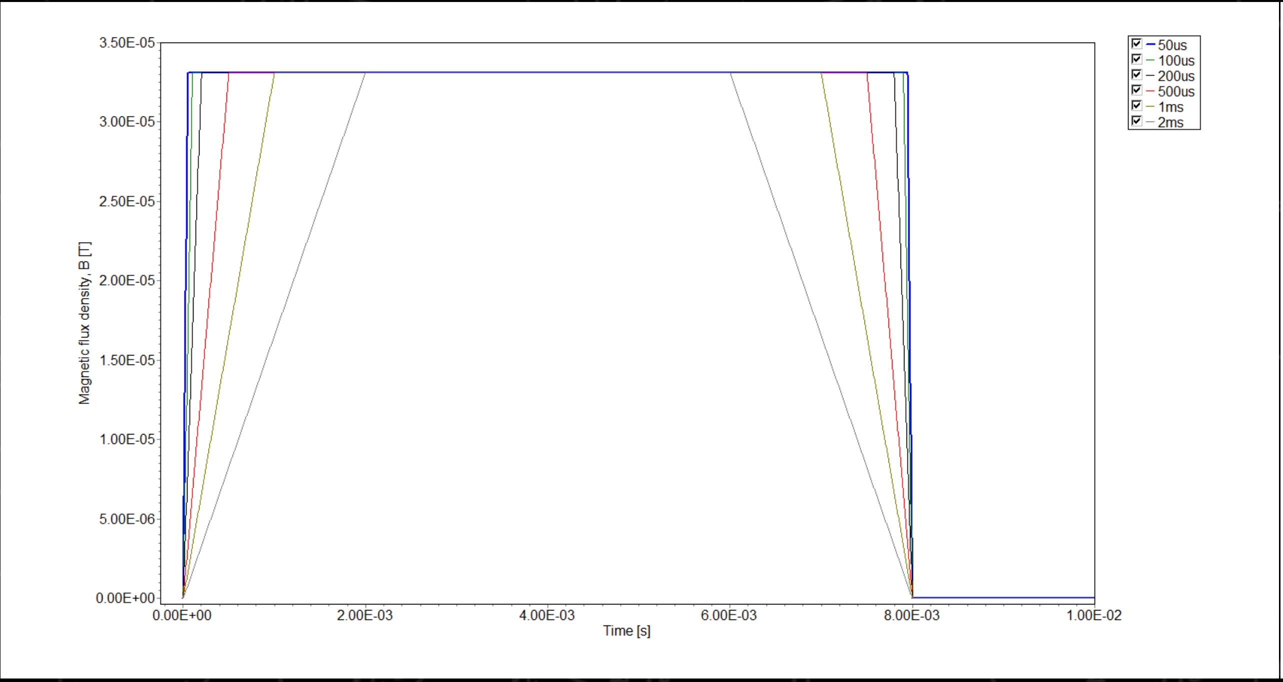
Computed ICNIRP GP 1998, exposure values

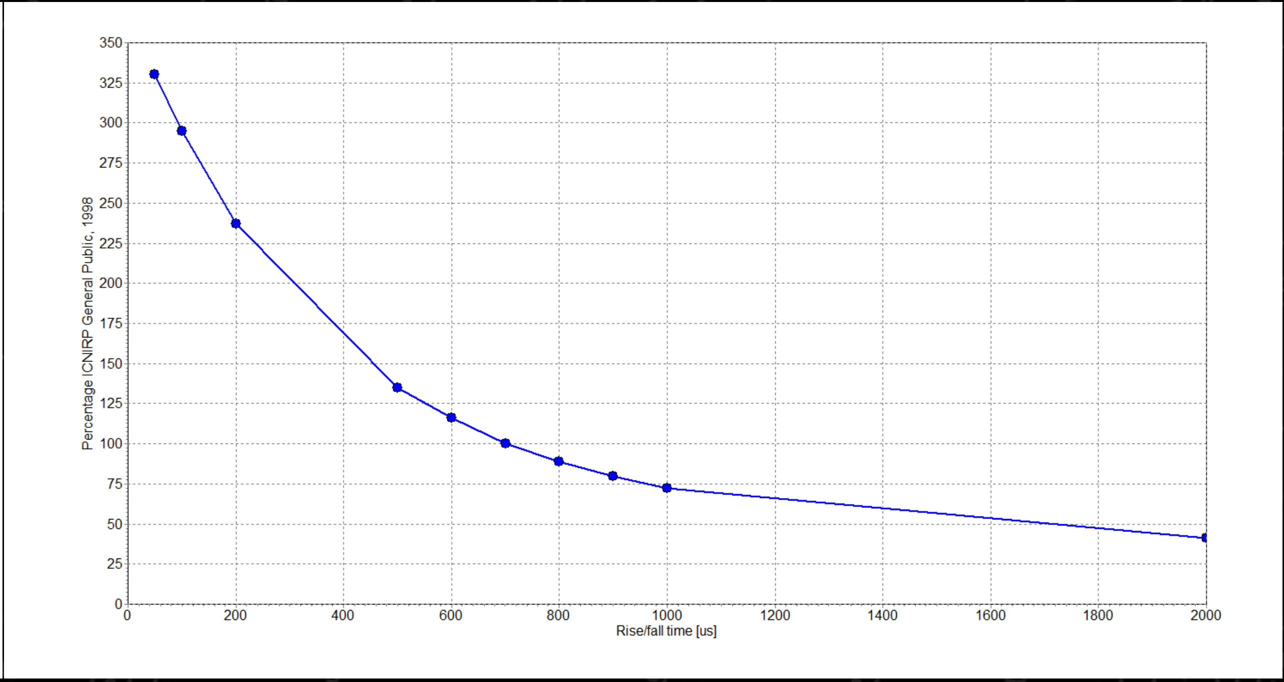
Switching frequency [Hz]	Duty cycle [%]	ICNIRP General public, 1998 [%]
33	30	65.5
33	50	65.5
33	70	65.6
33	90	65.7
100	30	65.5
100	50	65.4
100	70	65.5
100	90	65.3

Note: Requirement is an exposure value less than 100%

Discussion – Effect of Altering Rise/Fall Time

ICNIRP 1998 General Public as function of rise/fall time





Note: In this example, a rise/fall time larger than approx. 700 μs gives an ICNIRP value less than 100%.

Conclusions 1(2) – ICNIRP

- We have computed the ICNIRP General public 1998 exposure values for the worst case, i.e., configuration 3.
- We have computed the exposure at a distance of 40 mm from the heater, in reality we cannot measure closer than about 60-70 mm.
- We have assumed a PWM current with an amplitude of 16 A, switching frequencies 33 and 100 Hz, and a rise time of 1 µs. Four different duty cycles considered.
- Requirement is an exposure value less than 100%.

- Results shows that we have an exposure value less than 66% for the worst configuration
    - In principle, independent of duty cycle and the same for both 33 and 100 Hz switching frequency
    - Best configuration has an exposure value less than 26%

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Conclusions 2(2) – ICNIRP

- Exposure values are directly proportional to magnetic field amplitude, i.e., current amplitude.
  - Easy to scale to other currents than the used 16 A.
- The best configuration, configuration 2, gives less than half the field as compared to the analysed configuration 3. Thus, half exposure levels.
- The most important factor is the rise time of the current (field), the longer (slower) the better.
  - In the computations we have used 1 µs, which according to manufacturer should be considered as worst case. They mention 10 µs in the system (due to loading).

- All together, based on the presented analysis, the judgement is that the Air heater concept is safe in terms of magnetic field exposure
  - However, when the feeding cable type and layout is known the analysis is recommended to be complemented with computations of the field from the cable.

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Summary

- Simple simulation tools can be very helpful for concept studies and be of great help when making engineering judgements.

- Can be used when developing design guidelines (safety distance, placement, …).

- RE01 – The most important parameter is the PWM switching frequency.

- ICNIRP – The most important parameter is the rise/fall time for the PWM.

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