

Low frequency numerical dosimetry an overview

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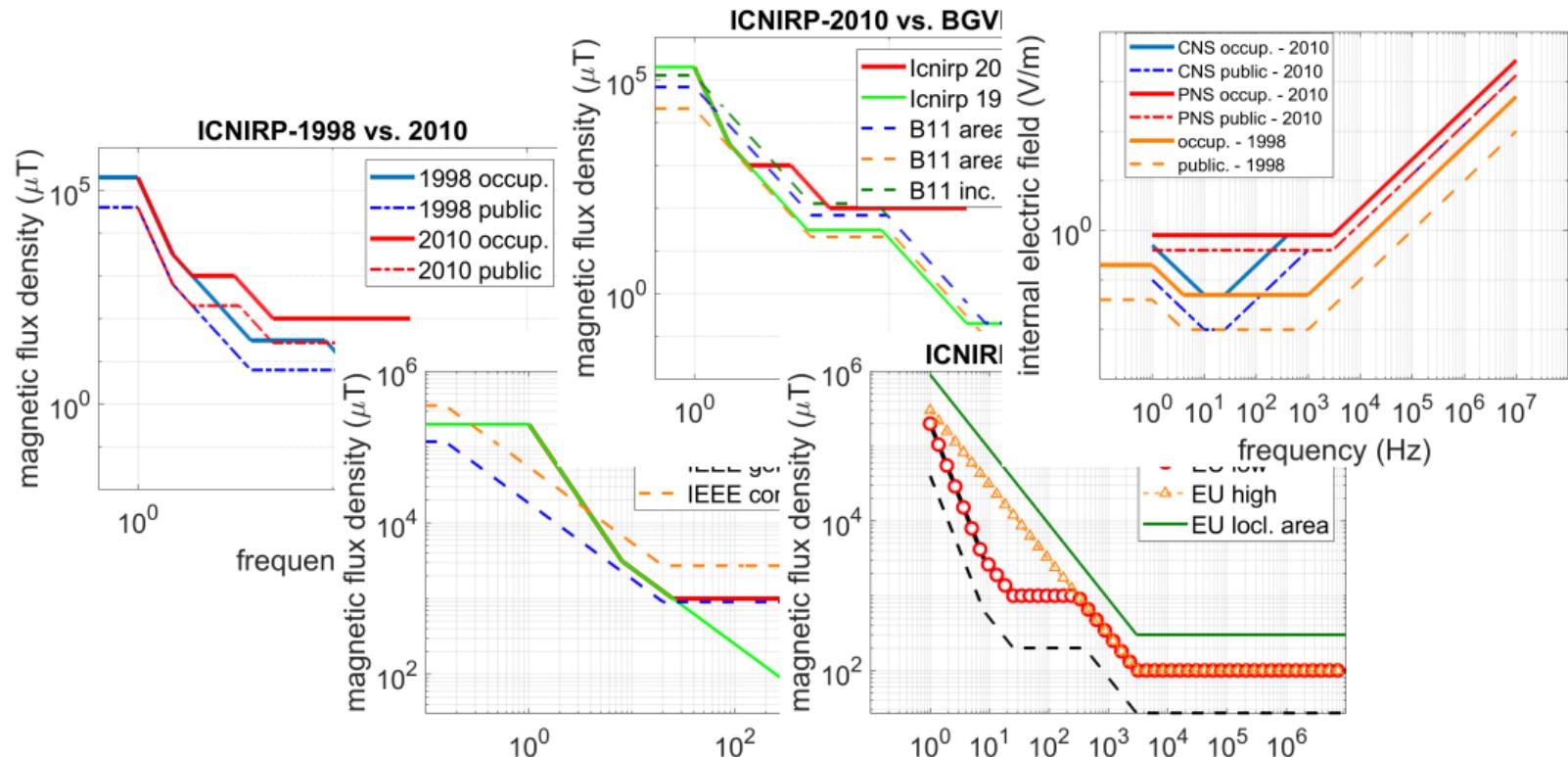
June 16, 2022

Outline

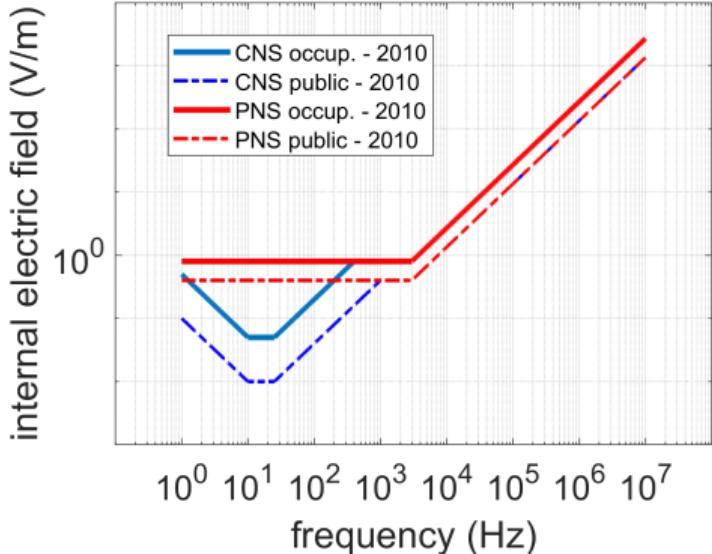
- ① Why we need to perform numerical dosimetry?
- ② How we can perform numerical dosimetry?
- ③ What human models can be used?
- ④ How can we model magnetic field sources?
- ⑤ Case study: dynamic WPT system

Why we need to perform numerical dosimetry?

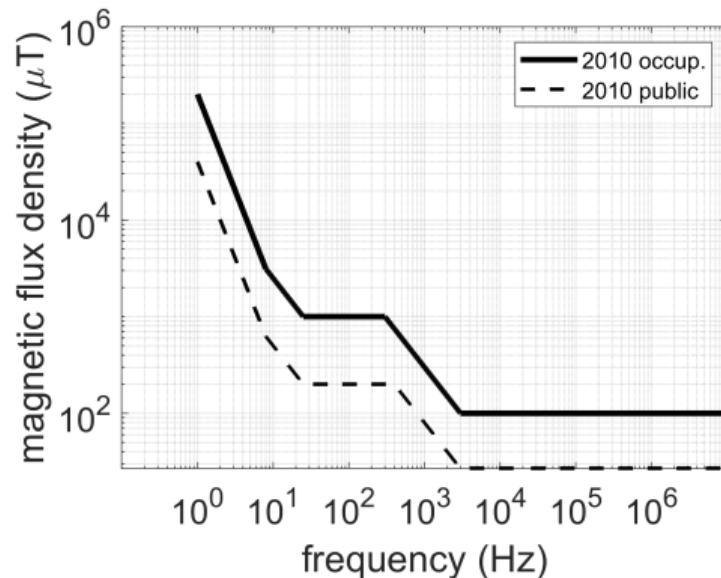
Because we have many standards and guidelines.



Reference levels



Basic restrictions: internal (induced) quantities directly related to stimulation.
Basic restrictions are not measurable.



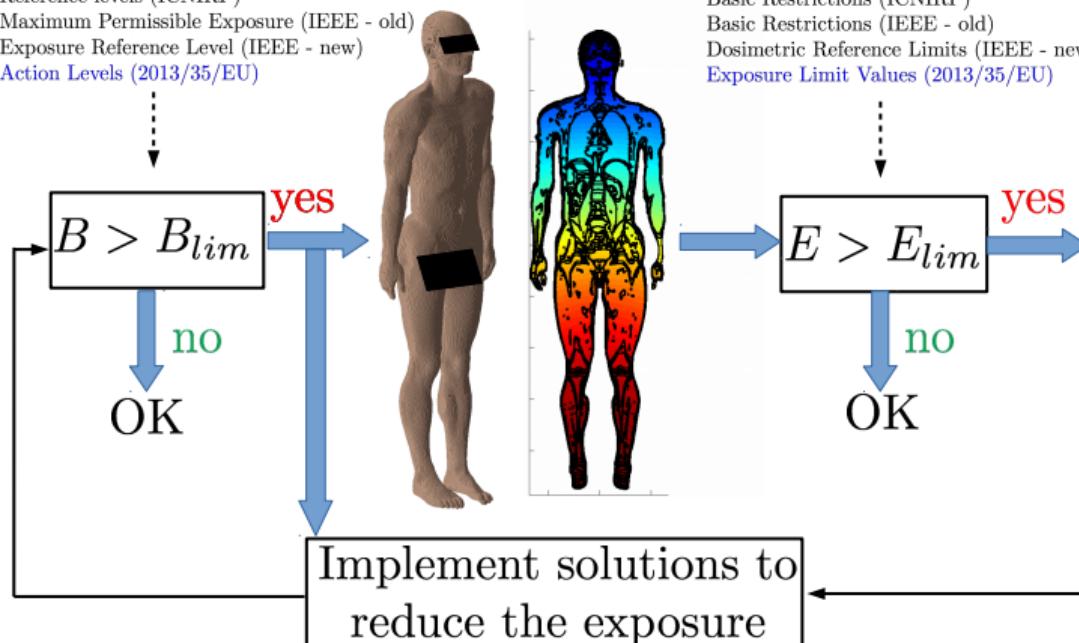
Reference Levels: external quantities that induce internal quantities. Reference Levels are measurable.

Exposure assessment strategy: two-step approach

- ① assess the *B*-field against *action levels*
- ② assess the *E*-field against *exposure limit values*

Reference levels (ICNIRP)
Maximum Permissible Exposure (IEEE - old)
Exposure Reference Level (IEEE - new)
Action Levels (2013/35/EU)

Basic Restrictions (ICNIRP)
Basic Restrictions (IEEE - old)
Dosimetric Reference Limits (IEEE - new)
Exposure Limit Values (2013/35/EU)



How we can perform numerical dosimetry?

$$\nabla \times \vec{H} = \vec{J} + \vec{J}_S \quad (1)$$

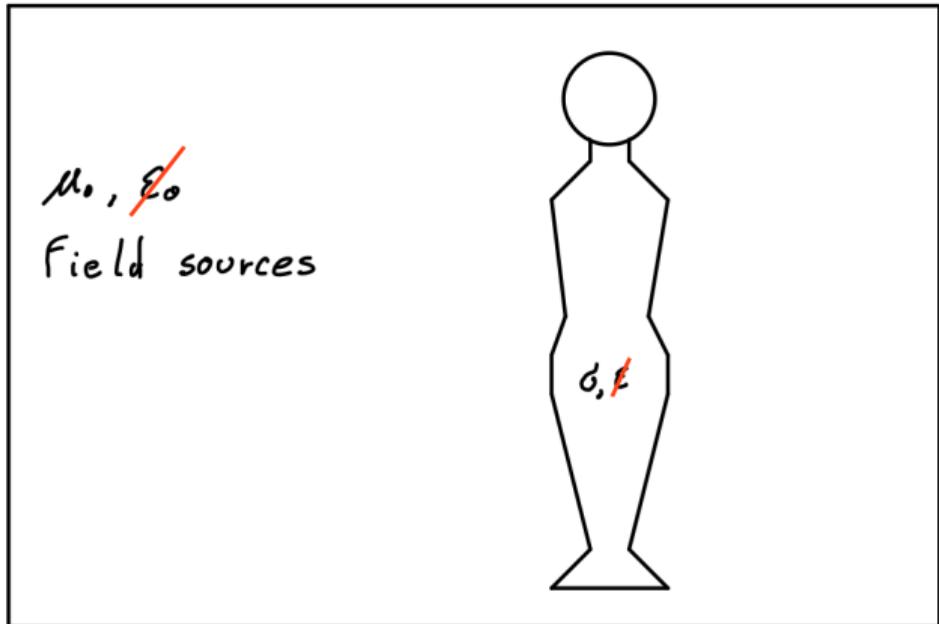
$$\nabla \cdot \vec{B} = 0 \quad (2)$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad (3)$$

$$\nabla \cdot \vec{J} = 0 \quad (4)$$

$$\vec{J} = \sigma \vec{E} \quad (5)$$

$$\vec{B} = \mu \vec{H} \quad (6)$$



How we can perform numerical dosimetry?

$$\nabla \times (\nabla \times \vec{A}) + \sigma \left(\nabla \varphi + \frac{\partial \vec{A}}{\partial t} \right) = \vec{J}_S \quad (7)$$

$$\nabla \cdot \left[\sigma \left(\nabla \varphi + \frac{\partial \vec{A}}{\partial t} \right) \right] = 0 \quad (8)$$

Tissue properties database

The screenshot shows a web browser window displaying the ITIS Foundation tissue properties database. The URL is <https://itis.swiss/virtual-population/tissue-properties/database/low-frequency-conductivity/>. The page has a dark theme with a red header banner containing the text "TISSUE PROPERTIES". Below the banner is a table of conductivity values for different tissues. A sidebar on the right lists various tissue properties and contact information. At the bottom, there are download links for "Virtual Population flyer" and "Virtual Animals flyer".

Low Frequency (Conductivity)

The following table contains values for the electrical conductivity for frequencies up to 1 MHz for all tissues, including statistical information on the standard deviation and the spread in the values. The low frequency parameters are based on a combination of the Gabriel dispersion relations¹ and a review of the available literature.

Note that if two values are drawn from the same publication, there will be a difference between the number of studies indicated in the table below and the number of references provided in the downloadable reference table.

Mixed: includes all studies (Across, Along), independent of the measured direction.

Skin: It has been reported that the conductivity of the skin significantly impacts the dosimetric assessment at low frequencies. The values for skin conductivity presented here should be used with caution.

Conductivity (S/m)	Average	Standard Deviation	Number of Studies	Minimum	Maximum
Adrenal Gland	4.81E-1	0.00E+0	1	4.81E-1	4.81E-1
Air	0.00E+0	0.00E+0	1	0.00E+0	0.00E+0
Bile	1.47E+0	2.80E-1	2	1.27E+0	1.67E+0
Blood	6.60E-1	1.39E-1	19	4.33E-1	9.46E-1

Database Summary

- Density
- Heat Capacity
- Thermal Conductivity
- Heat Transfer Rate
- Heat Generation Rate
- Dielectric Properties
- Tissue Frequency Chart
- Low Frequency (Conductivity)**
- Viscosity
- Relaxation Times
- Acoustic Properties
- Elemental Composition

CONTACT INFORMATION

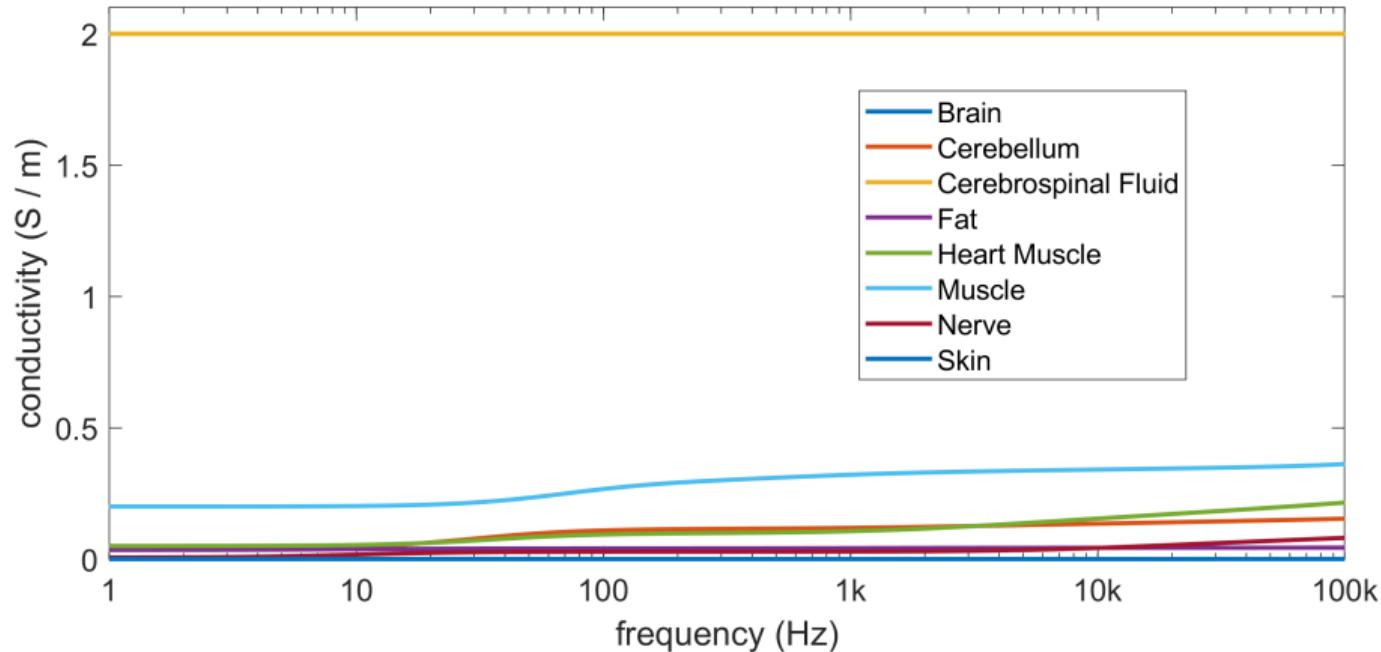
Bryn A. Lloyd
virtualpopulation@itis.swiss

DOWNLOADS

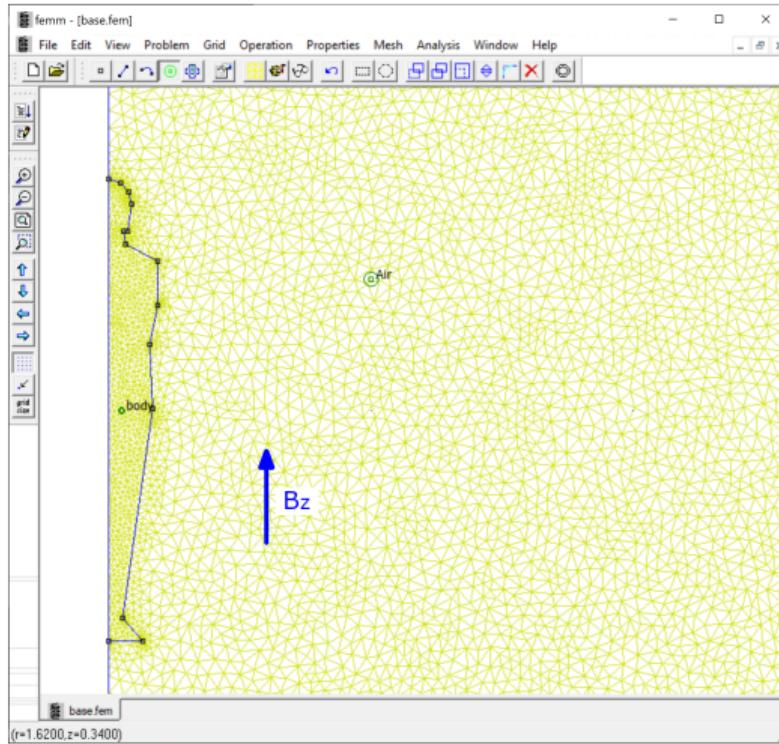
[Virtual Population flyer](#)
[Virtual Animals flyer](#)

direct link

Sigma vs frequency



Influence of the conductivity

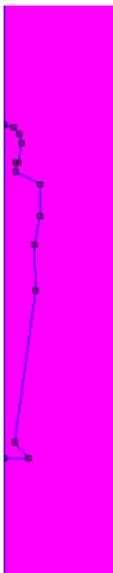


- $f = 100 \text{ kHz}$
- B homogeneous,
 $27 \mu\text{T}$ in z direction
- σ : variable from
 0.2 S/m to
 200000 S/m

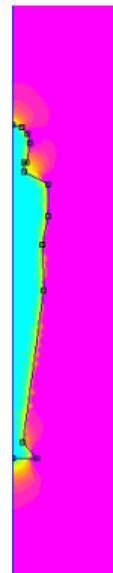
Influence of the conductivity



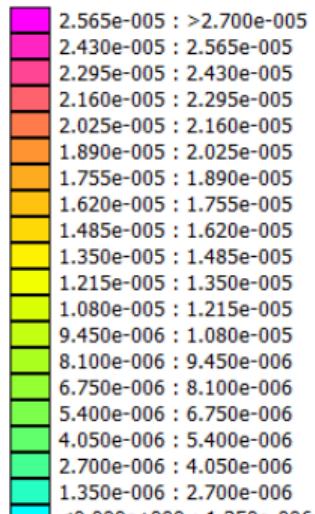
(a)
0.2 (S/m)



(b)
200 (S/m)

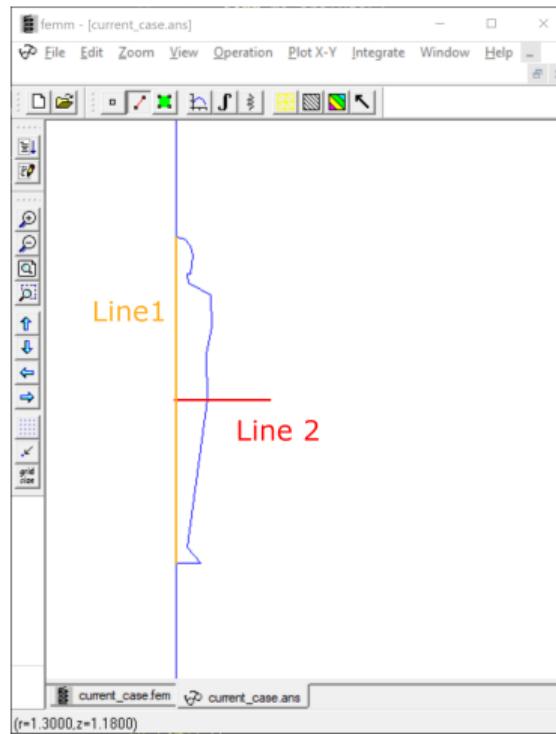


(c)
200000 (S/m)



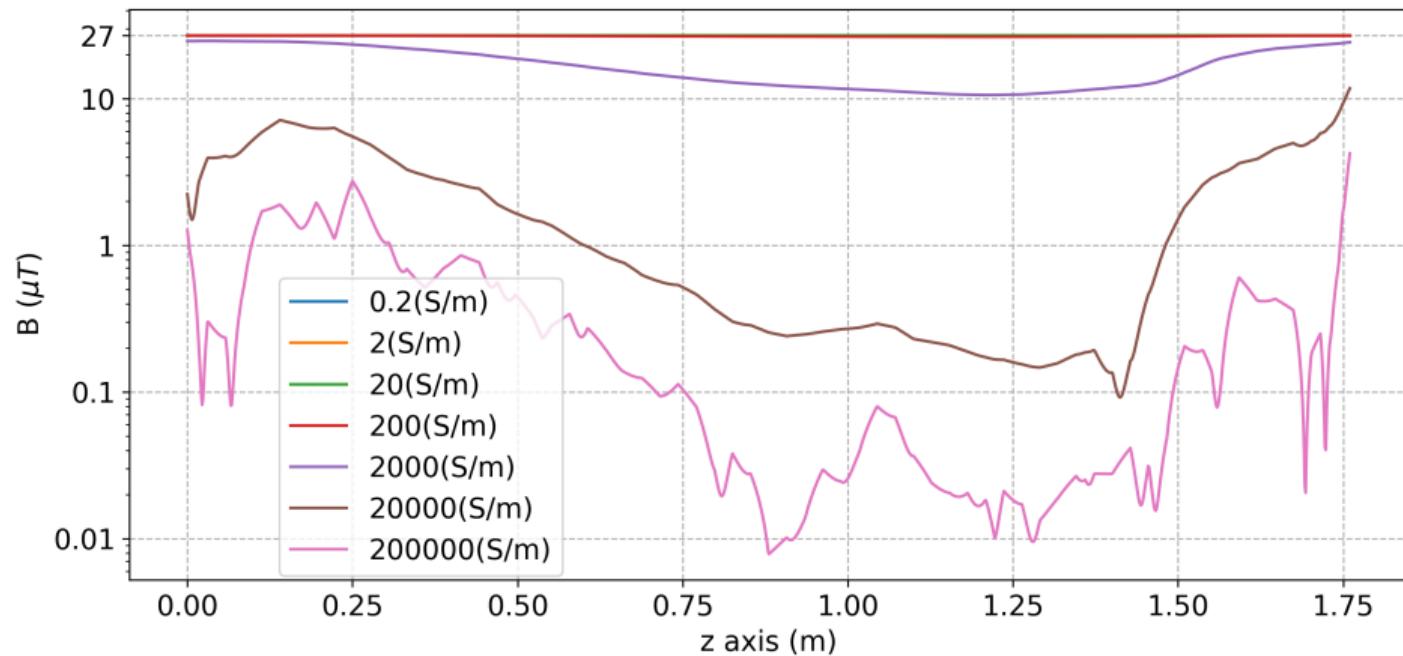
Density Plot: $|B|$, Tesla

Influence of the conductivity

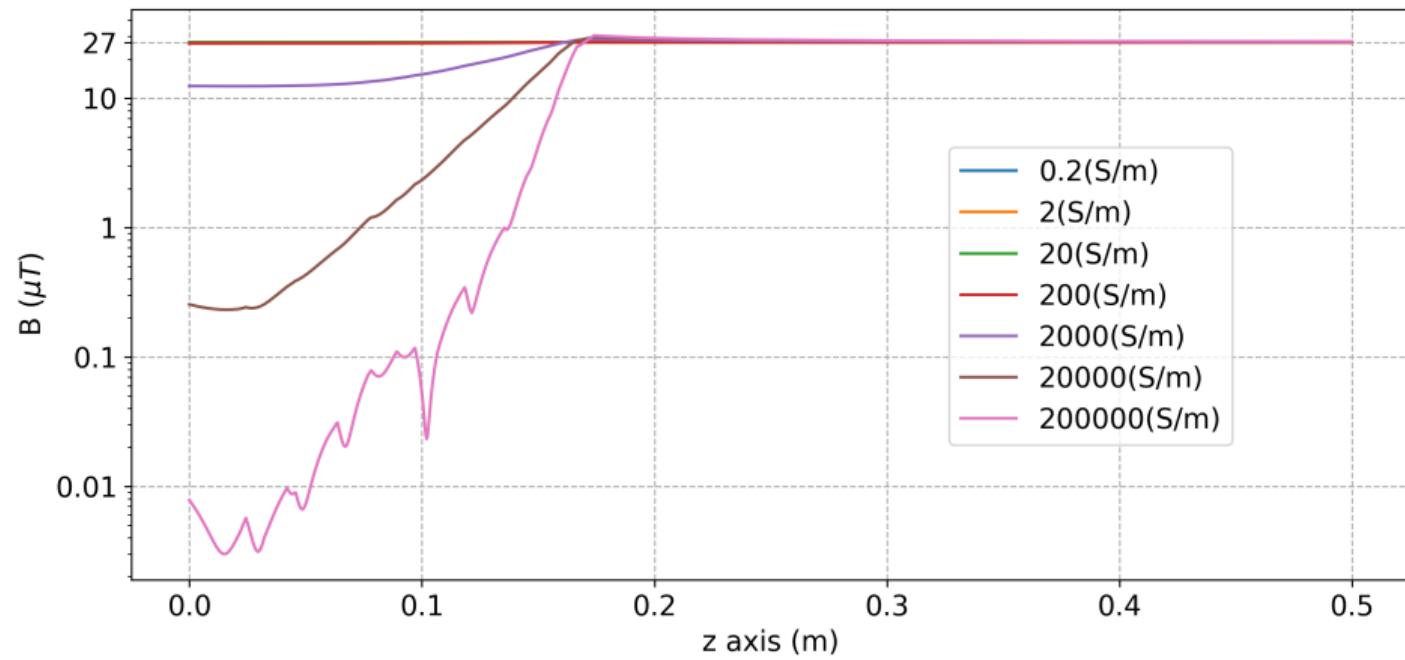


- line 1: z direction
- line 2: radial direction

Influence of the conductivity



Influence of the conductivity



Scalar Potential Finite Difference

- Under the hypothesis of unperturbed external field, the only unknown becomes the electric scalar potential φ .
- it can be computed using the equation:

$$\nabla \cdot (\sigma \nabla \varphi) = -\nabla \cdot \left(\sigma \frac{\partial A}{\partial t} \right) \quad (9)$$

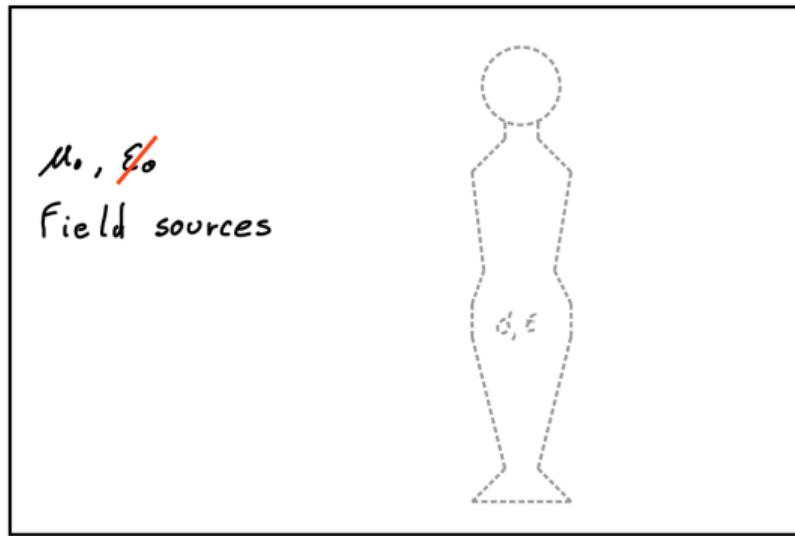
- once φ is computed, internal electric field and/or current density are computed as:

$$E = -\nabla \varphi - \frac{\partial A}{\partial t} \quad (10)$$

$$J = \sigma E \quad (11)$$

Scalar Potential Finite Difference

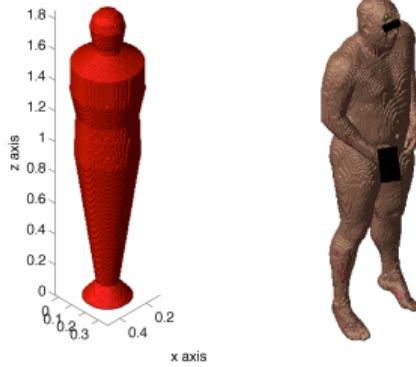
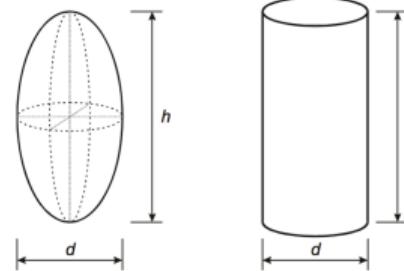
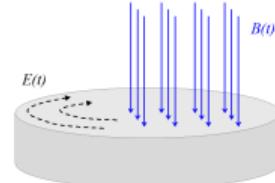
First step: simulation of the source without the human model



Second step: dosimetric problem considering only the human model



Human body models

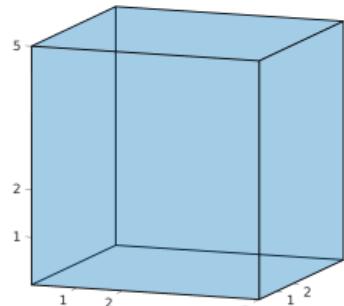
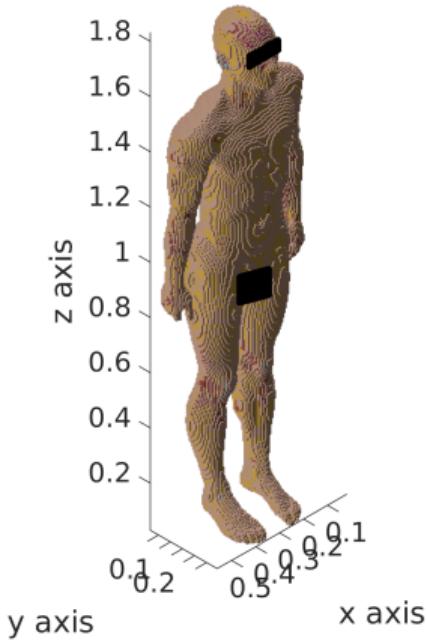


Human body models



How about the number of unknown?

$$\nabla \cdot (\sigma \nabla \varphi) = -\nabla \cdot \left(\sigma \frac{\partial A}{\partial t} \right)$$



primal =

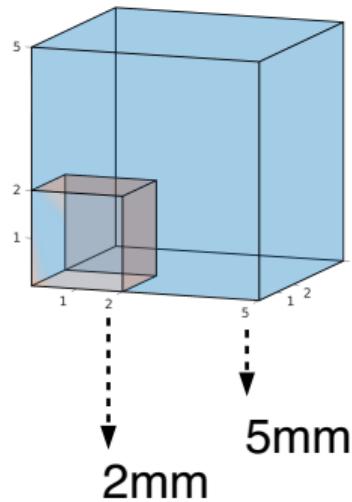
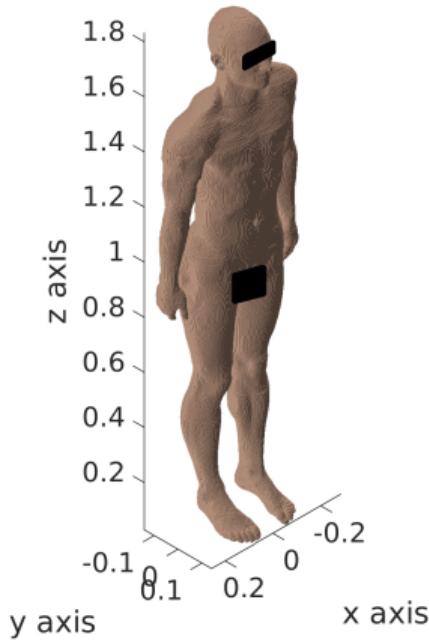
struct with fields:

Node: [600675x3 double]
Vol2Nod: [548164x8 int32]
Object: [548164x1 int32]
Symmetry: [0 0 0]
Scale: 1
ElementType: 'Brk'
Edg2Nod: [1748469x2 int32]
Fac2Nod: [1695945x4 int32]
Fac2Edg: [1695945x4 int32]
Vol2Fac: [548164x6 int32]
Vol2Edg: [548164x12 int32]

600k

How about the number of unknown?

$$\nabla \cdot (\sigma \nabla \varphi) = -\nabla \cdot \left(\sigma \frac{\partial A}{\partial t} \right)$$



primal =

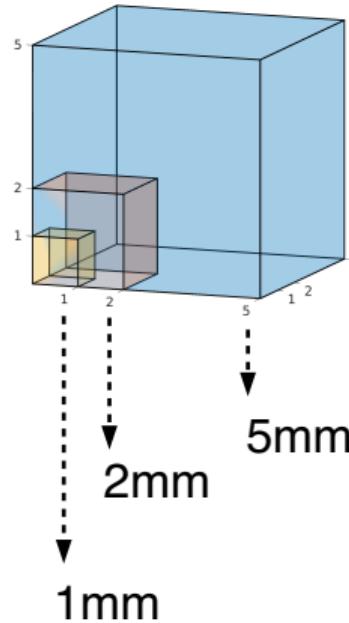
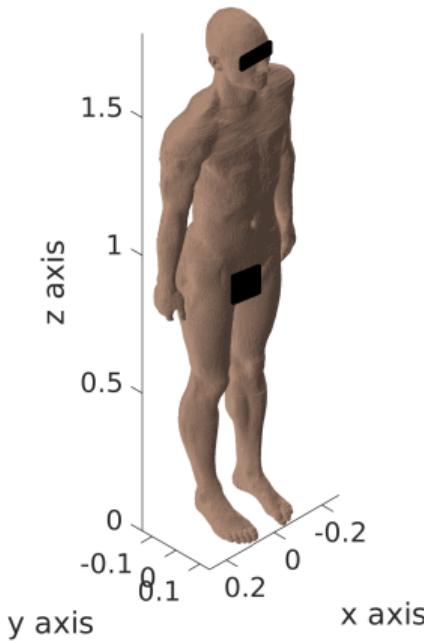
struct with fields:

Node: [8894788x3 double]
Vol2Nod: [8567702x8 int32]
Object: [8567702x1 int32]
Symmetry: [0 0 0]
Scale: 1
ElementType: 'Brk'
Edg2Nod: [26354352x2 int32]
Fac2Nod: [26027234x4 int32]
Fac2Edg: [26027234x4 int32]
Vol2Fac: [8567702x6 int32]
Vol2Edg: [8567702x12 int32]

9M

How about the number of unknown?

$$\nabla \cdot (\sigma \nabla \varphi) = -\nabla \cdot \left(\sigma \frac{\partial A}{\partial t} \right)$$



primal =

struct with fields:

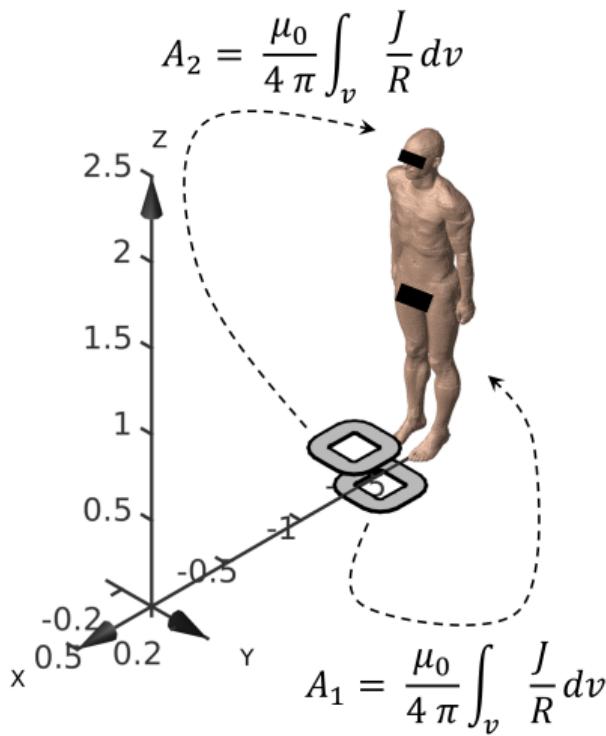
```
Node: [69855415x3 double]
Vol2Nod: [68549358x8 int32]
Object: [68549358x1 int32]
Symmetry: [0 0 0]
Scale: 1
ElementType: 'Brk'
Edg2Nod: [208254525x2 int32]
Fac2Nod: [206948603x4 int32]
Fac2Edg: [206948603x4 int32]
Vol2Fac: [68549358x6 int32]
Vol2Edg: [68549358x12 int32]
```

70M

How do we compute the right hand side?

$$\nabla \cdot (\sigma \nabla \varphi) = -\nabla \cdot \left(\sigma \frac{\partial A}{\partial t} \right)$$

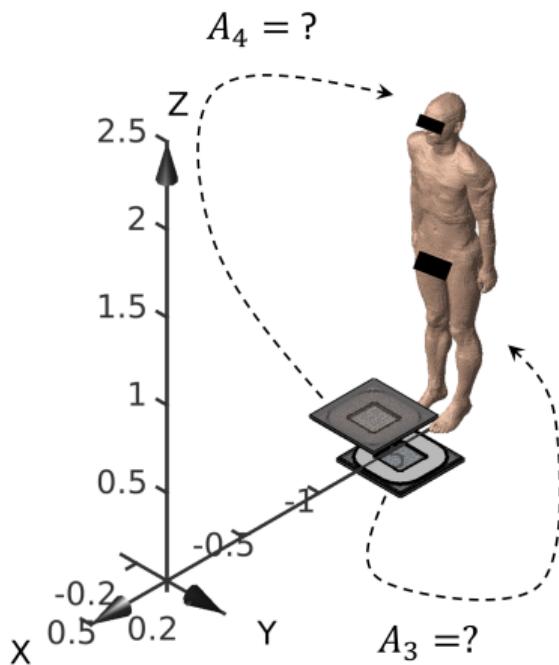
How do we compute the right hand side?



Example 1: WPT system made of two coils (transmitter and receiver)

- the problem is linear
- superposition can be exploited
- considering the example of two coils, the magnetic vector potential is computed separately for each coil
- the best way to simulate this kind of source it an integral technique that does not need to discretize the air

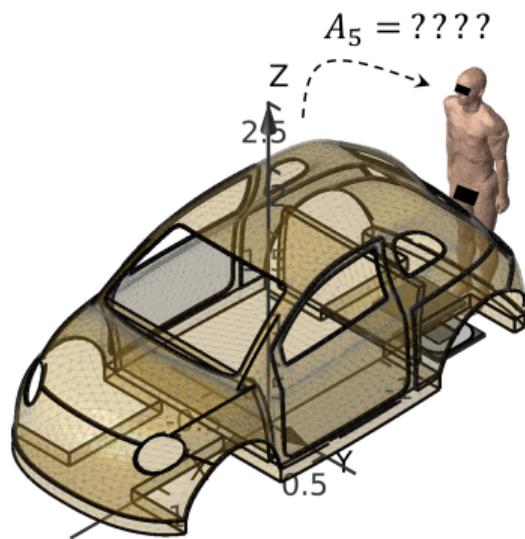
How do we compute the right hand side?



Example 2: WPT system made of two coils
+ Aluminum + Ferrite.

- the problem is still linear
- superposition can be still exploited
- we need to add the contribution of the metallic material (Aluminum + Ferrite).
- sometimes the best formulation to solve this problem does not provide the magnetic vector potential

How do we compute the right hand side?



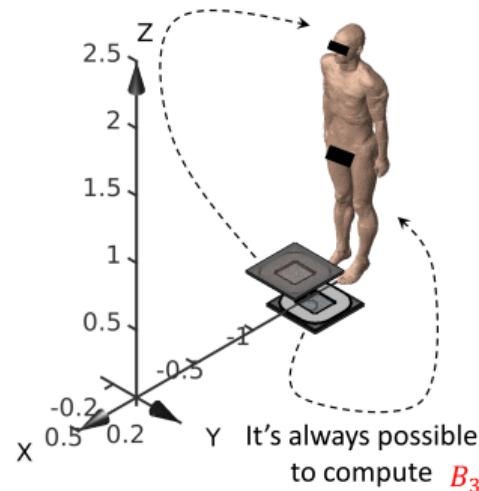
Example 3: WPT system made of two coils
+ Aluminum + Ferrite + car body.

- the problem is still linear
- superposition can be still exploited
- we need to add the contribution of the cab body.
- again, *sometimes the best formulation to solve this problem does not provide the magnetic vector potential*

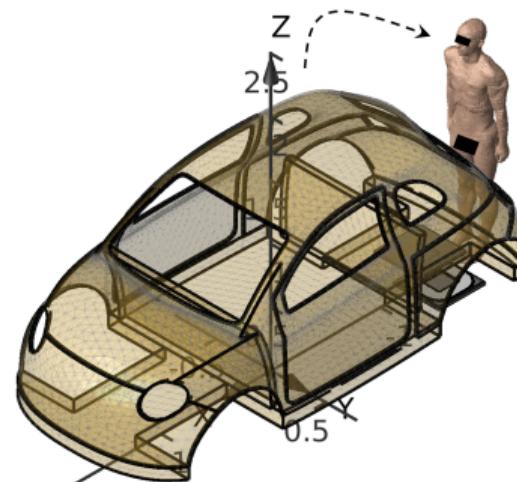
How do we compute the right hand side?

It is worth noting that the computation of the magnetic flux density is always possible with all formulations and software.

It's always possible
to compute B_4



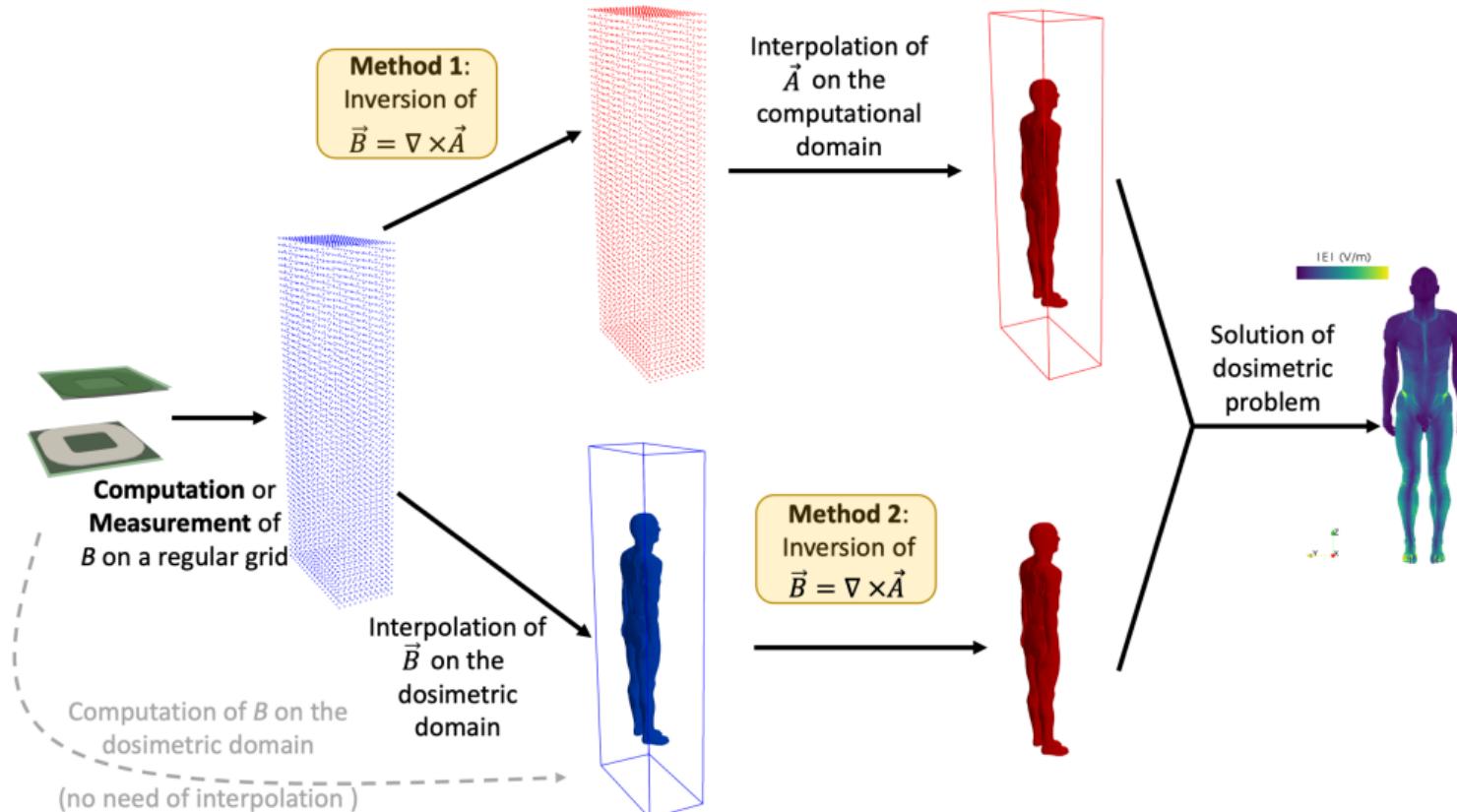
It's always possible
to compute B_5



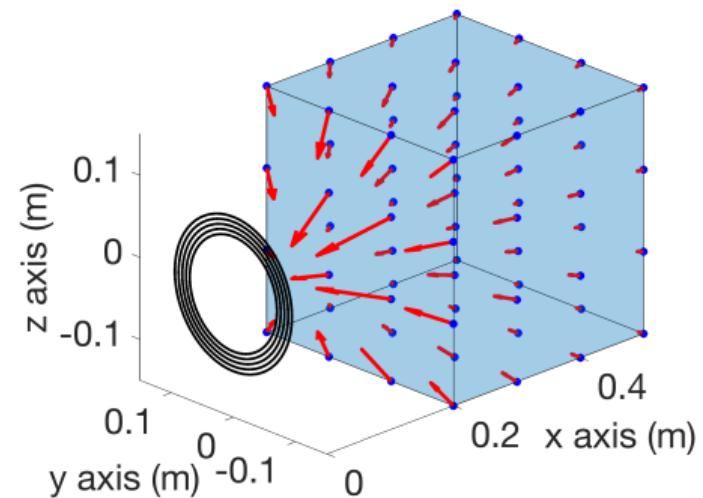
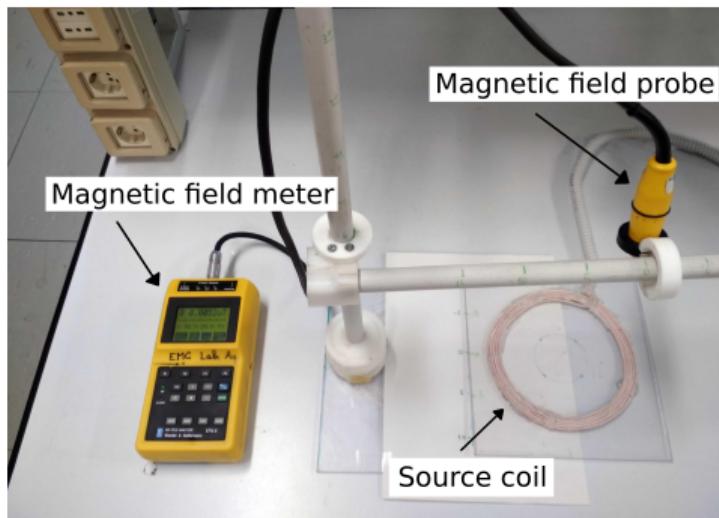
Is it possible to compute \vec{A} from \vec{B} ?

- [1] Laakso, I., De Santis, V., Cruciani, S., Campi, T. and Feliziani, M. (2017) Modelling of induced electric fields based on incompletely known magnetic fields. *Physics in Medicine and Biology*, 62 (16).
- [2] Freschi, F., Giaccone, L., Cirimele, V., and Canova, A. (2018). Numerical assessment of low-frequency dosimetry from sampled magnetic fields. *Physics in Medicine and Biology*, 63(1).
- [3] Conchin Gubernati, A., Freschi, F., Giaccone, L., Campi, T., De Santis, V., and Laakso, I. (2019). Comparison of numerical techniques for the evaluation of human exposure from measurement data. *IEEE Transactions on Magnetics*, 55(6).

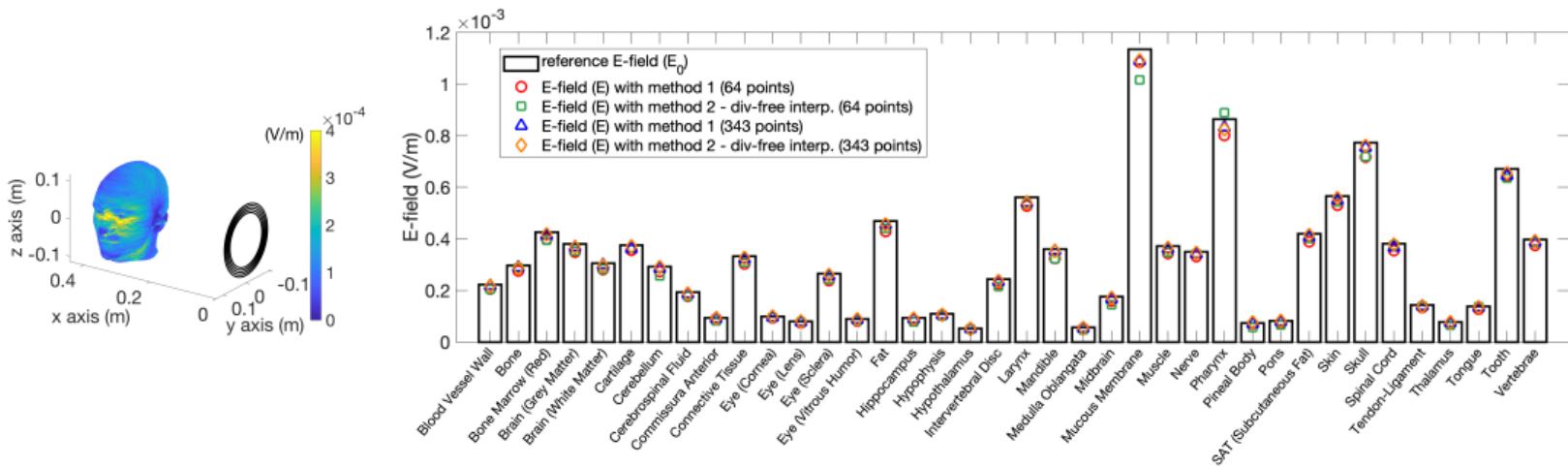
Is it possible to compute \vec{A} from \vec{B} ?



Method 1 vs Method 2



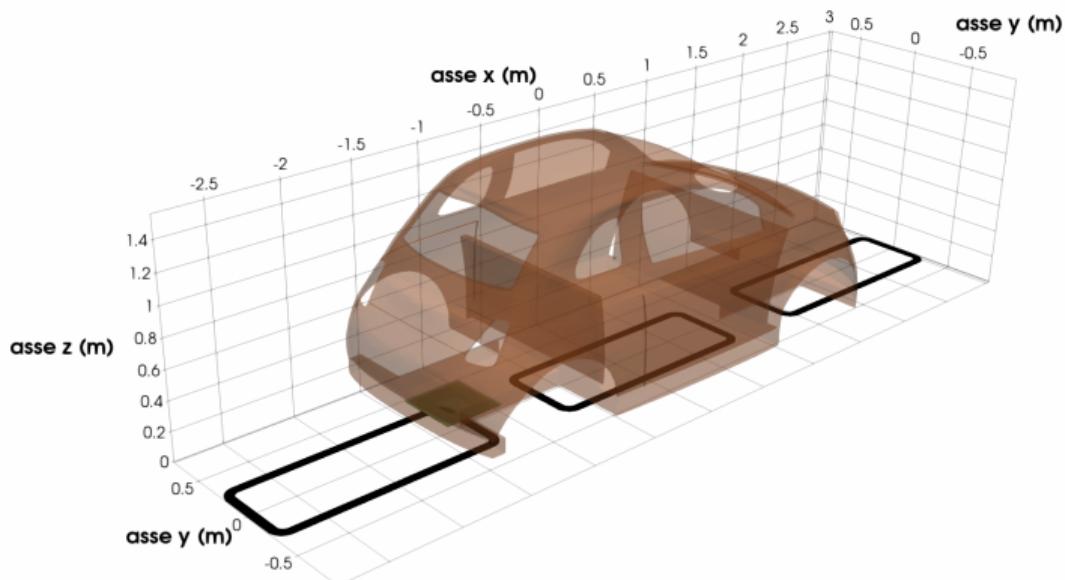
Method 1 vs Method 2



Case study: dynamic WPT system

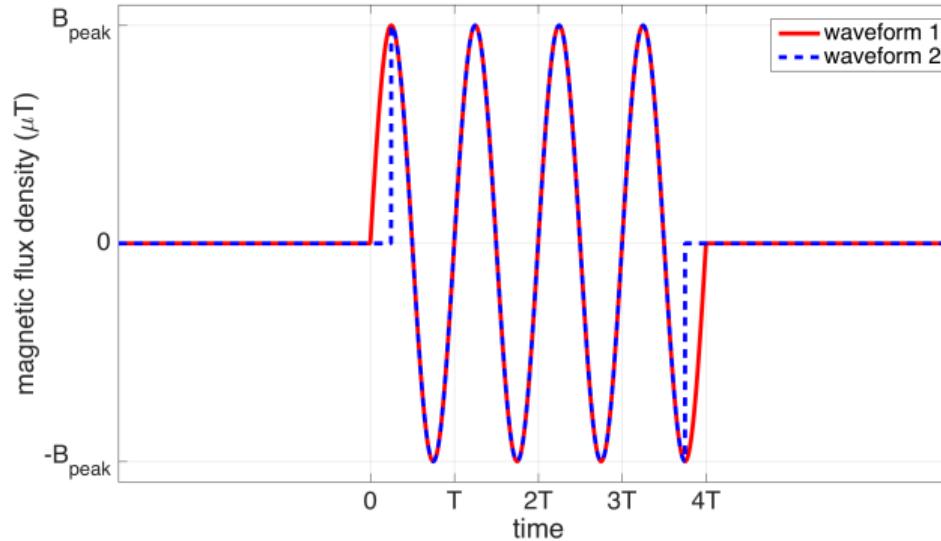
Charge while driving

- frequency 85 kHz
- (max) power 7.7 kW
- 50 transmitters:
 - 1.5 m length, 0.5 m wide, 0.5 m gap
 - 26 A
 - 10 number of turns
- 1 receiver
 - based on standard SAE J2954
 - rear position
 - 13 A
 - 10 turns



Simplifying conditions

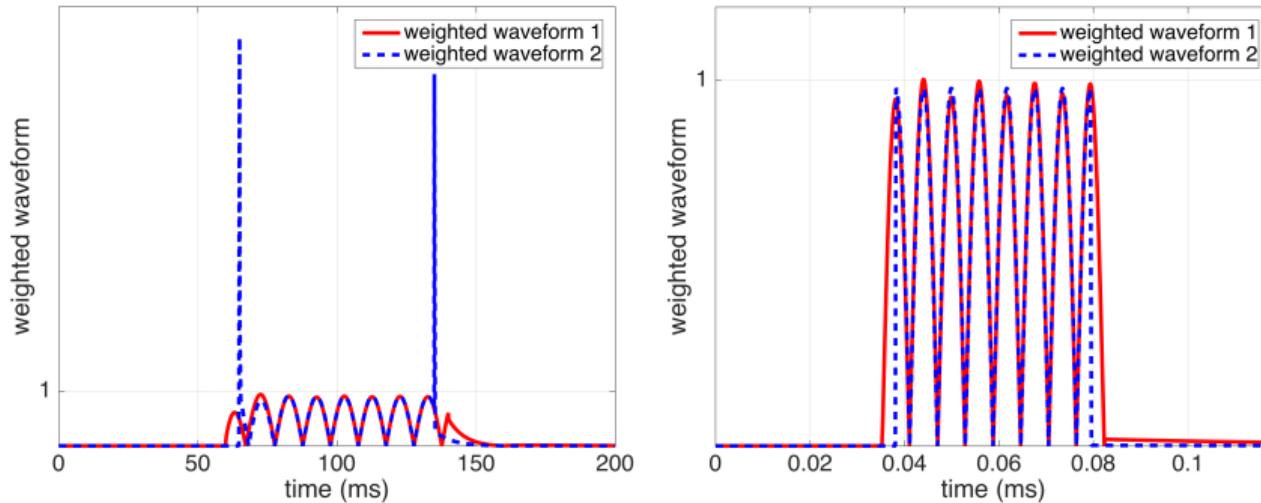
- ① dynamic effects due to the motion of the vehicle are negligible¹
- ② exposure is pulsed but can be considered as steady state



¹Di Capua, et. al "Analysis of dynamic wireless power transfer systems based on behavioral modeling of mutual inductance", (2021) Sustainability, 13 (5), art. no. 2556, pp. 1-15, DOI: 10.3390/su13052556

Simplifying conditions

- ① dynamic effects due to the motion of the vehicle are negligible¹
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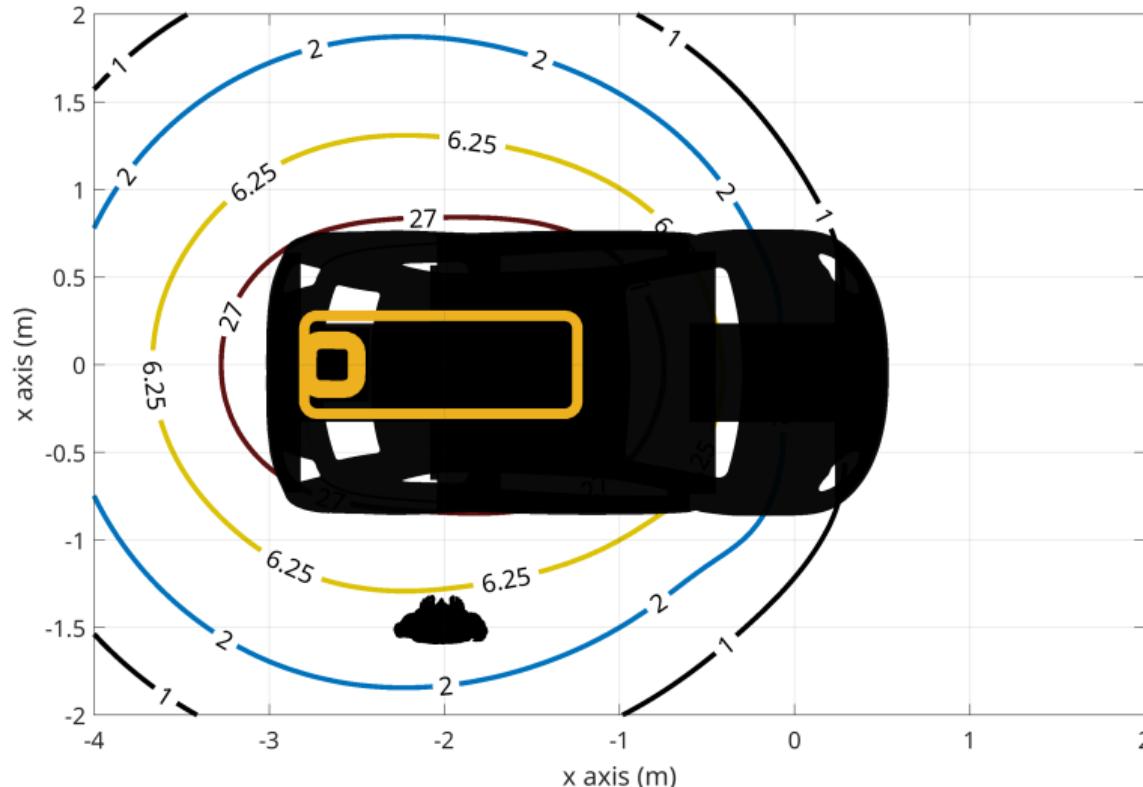
¹Di Capua, et. al "Analysis of dynamic wireless power transfer systems based on behavioral modeling of mutual inductance", (2021) Sustainability, 13 (5), art. no. 2556, pp. 1-15, DOI: 10.3390/su13052556

Simplifying conditions

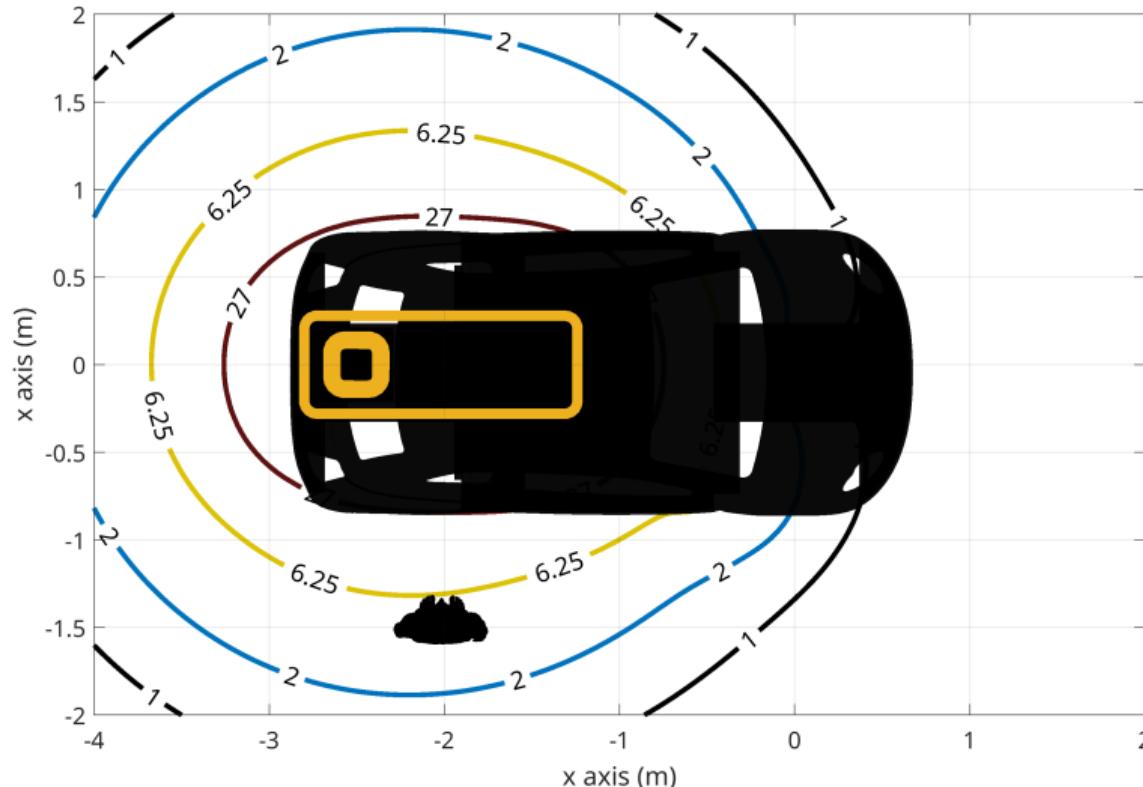
- ① dynamic effects due to the motion of the vehicle are negligible¹
 - ② exposure is pulsed but can be considered as steady state
-
- It is possible to study a Dynamic-WPT with all methods suitable for a stationary WPT.
 - Due to the motion of the vehicle the worst case conditions have to be defined.

¹Di Capua, et. al "Analysis of dynamic wireless power transfer systems based on behavioral modeling of mutual inductance", (2021) Sustainability, 13 (5), art. no. 2556, pp. 1-15, DOI: 10.3390/su13052556

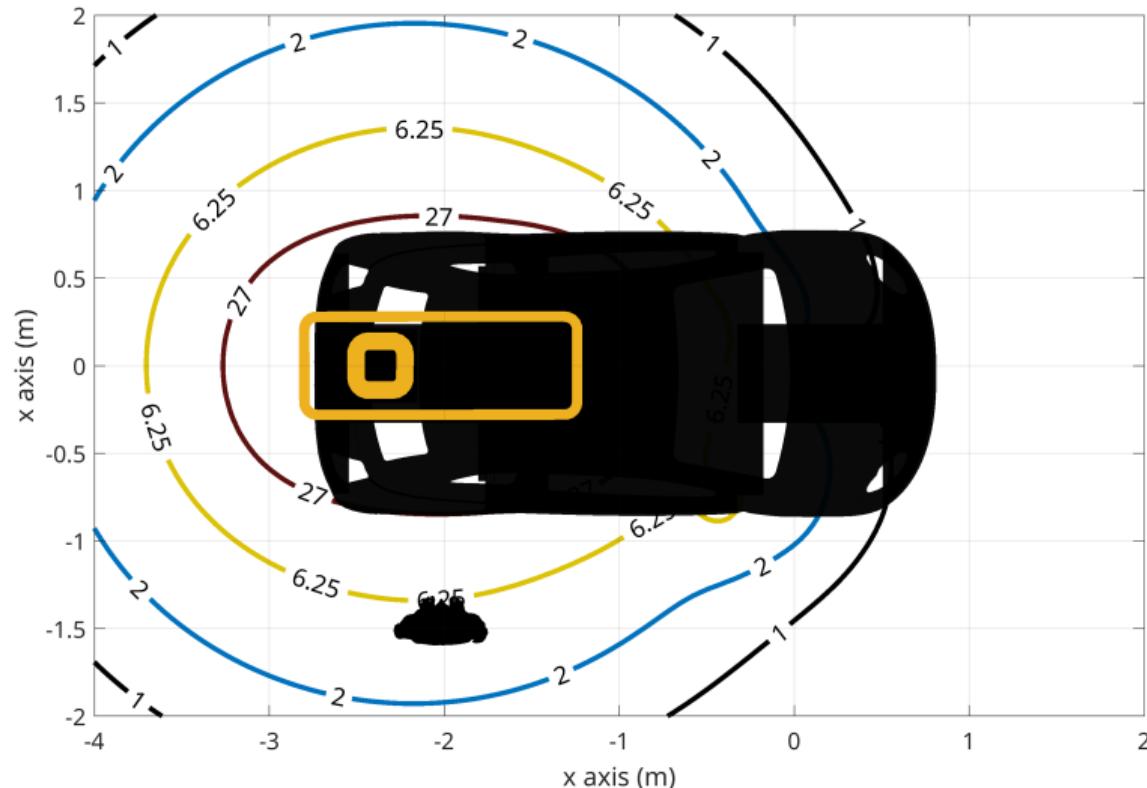
Magnetic flux density vs motion



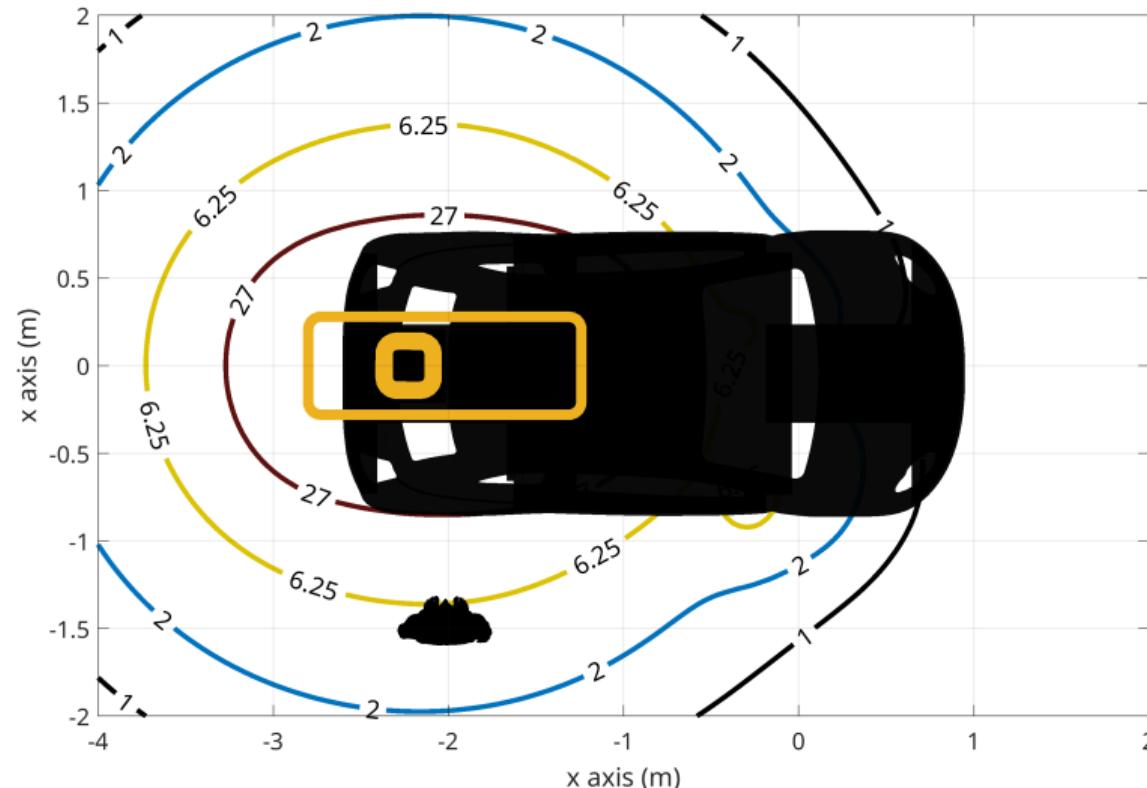
Magnetic flux density vs motion



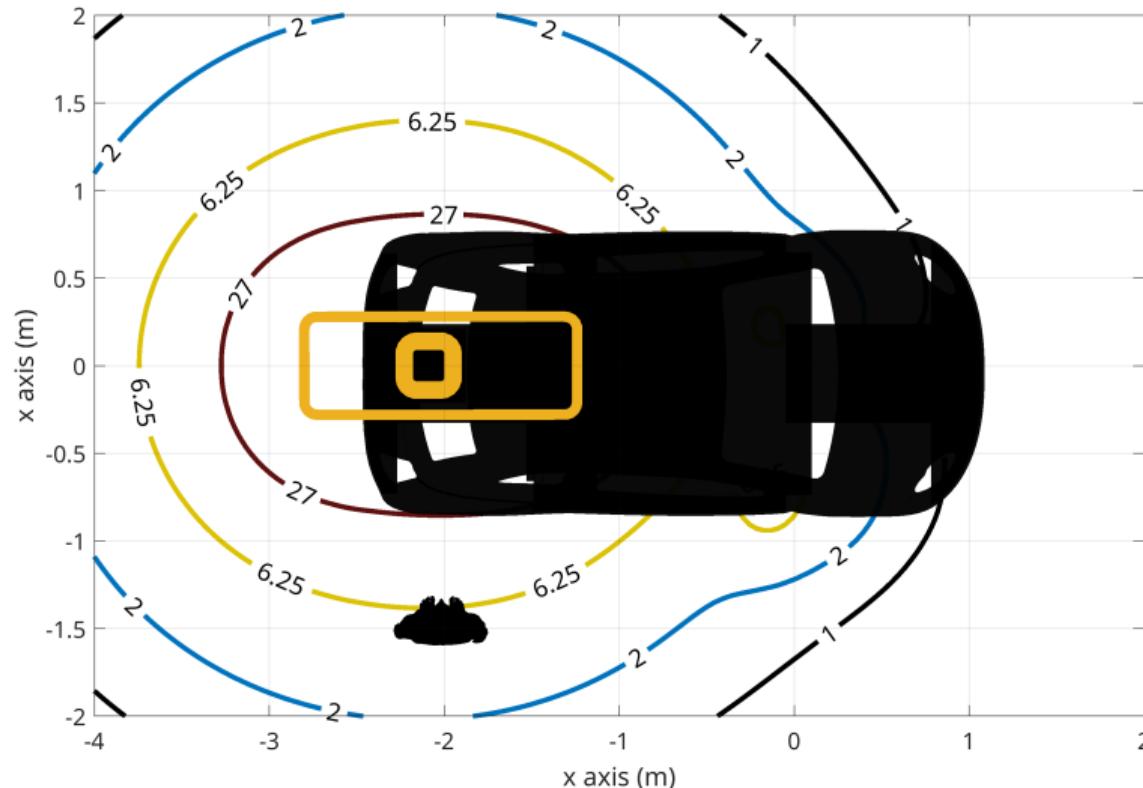
Magnetic flux density vs motion



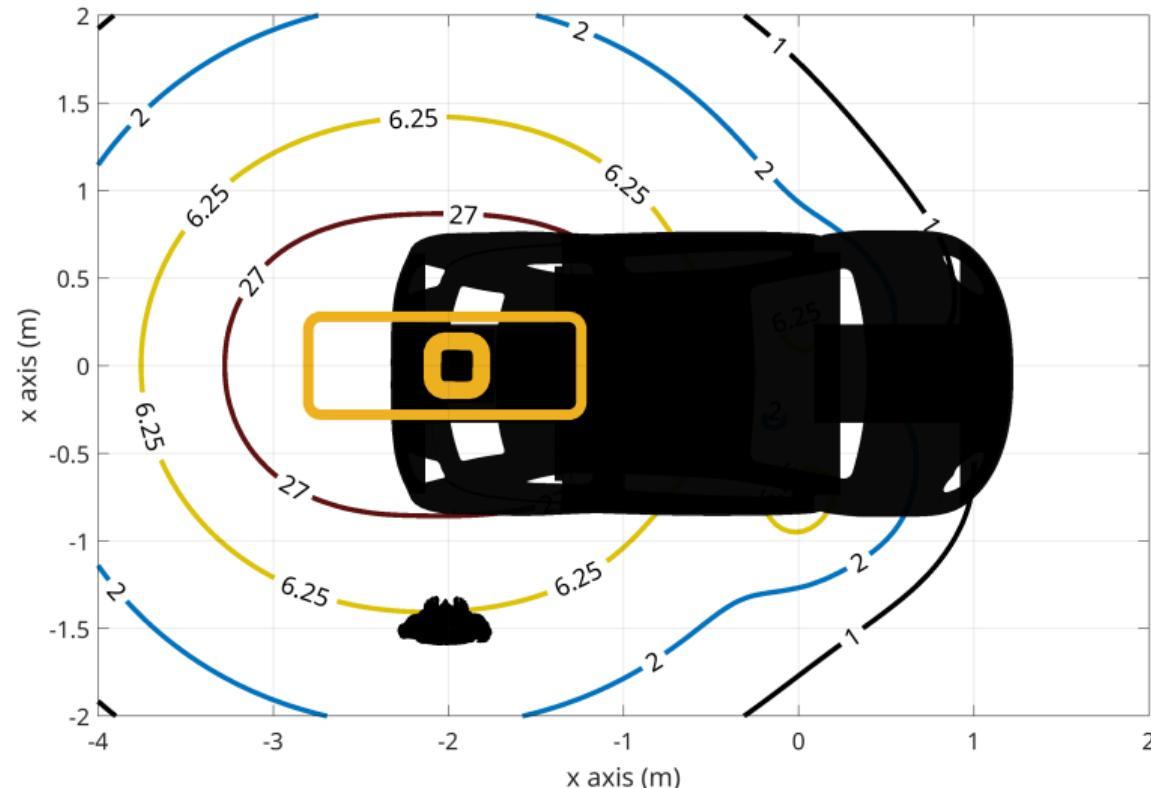
Magnetic flux density vs motion



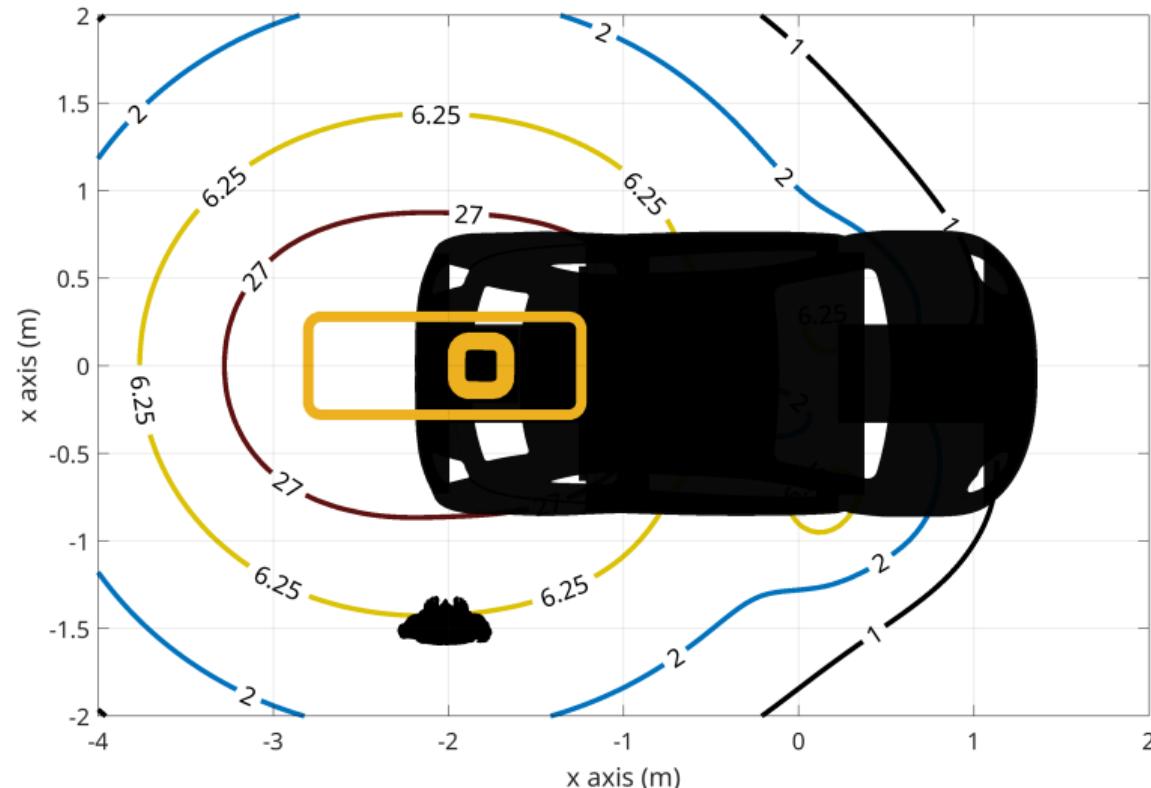
Magnetic flux density vs motion



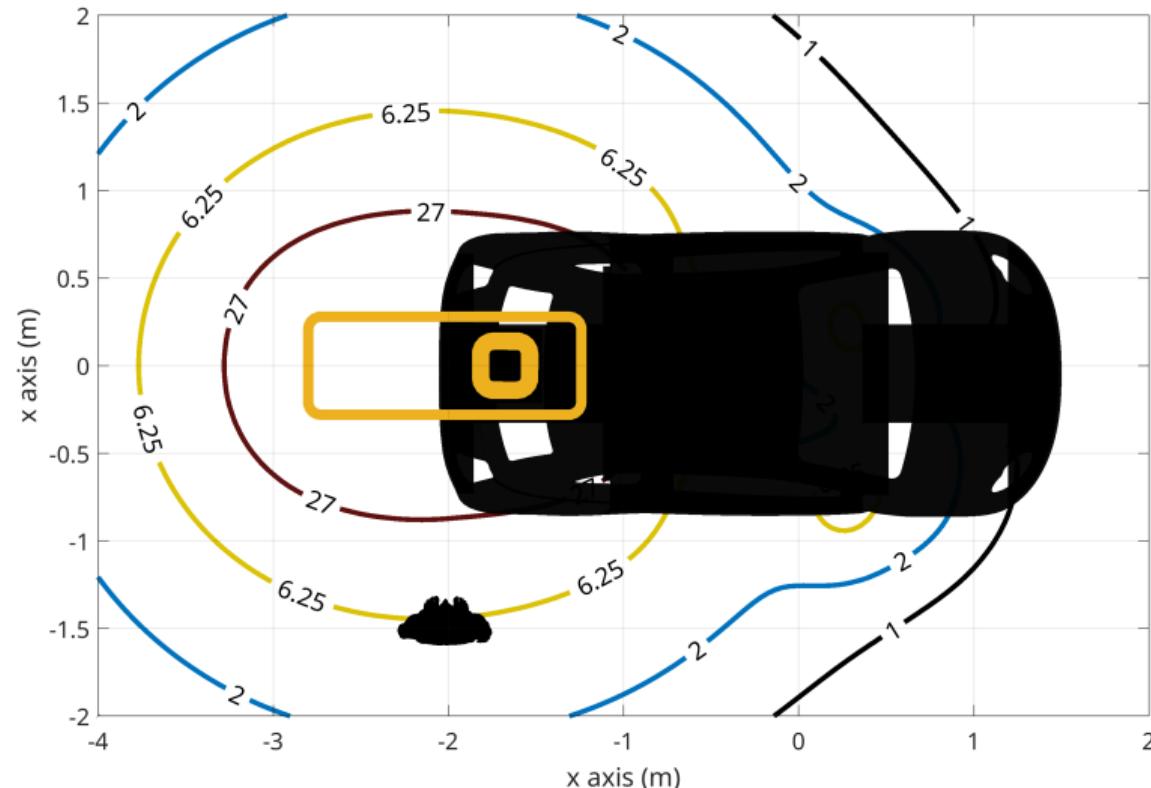
Magnetic flux density vs motion



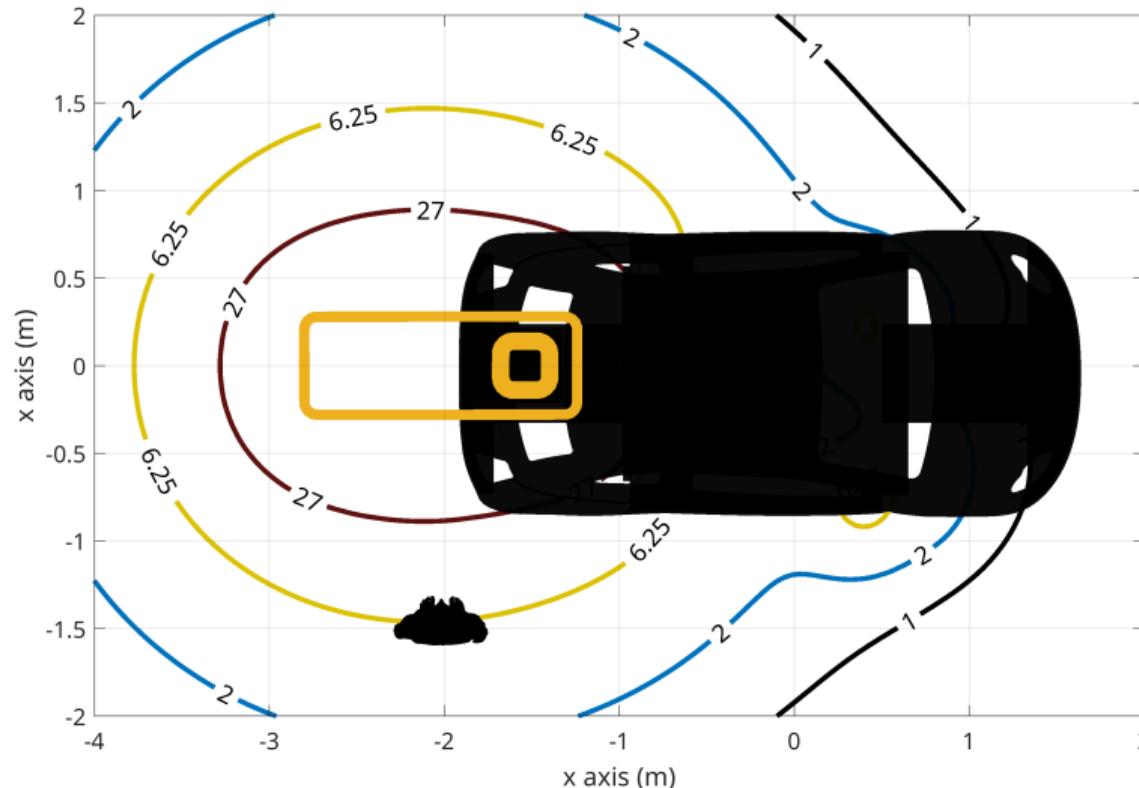
Magnetic flux density vs motion



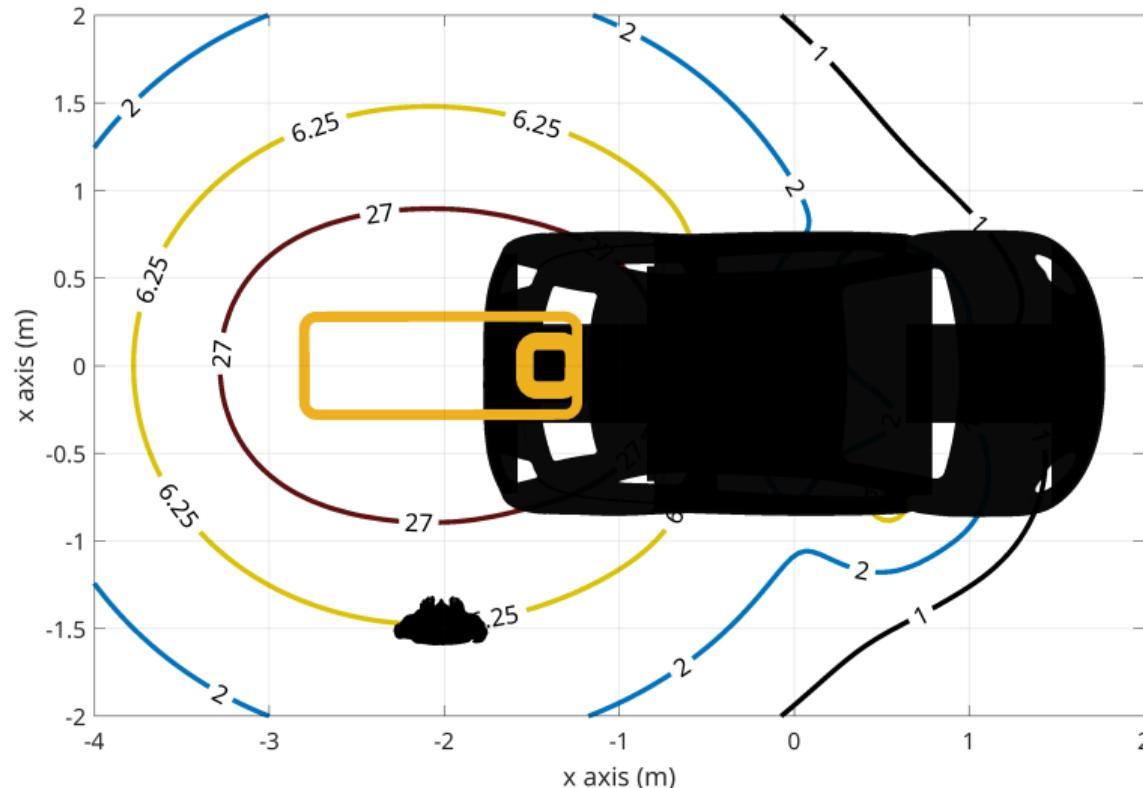
Magnetic flux density vs motion



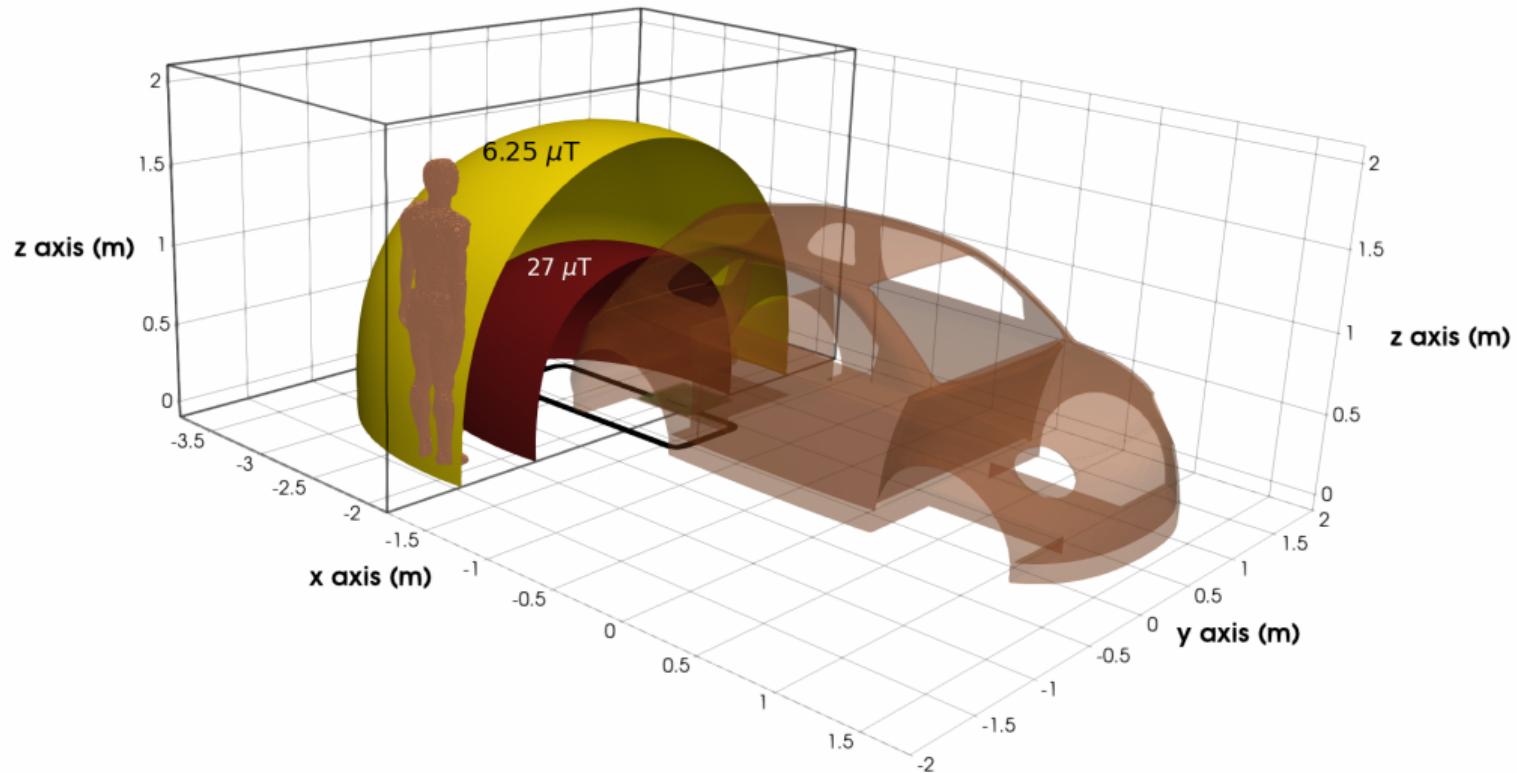
Magnetic flux density vs motion



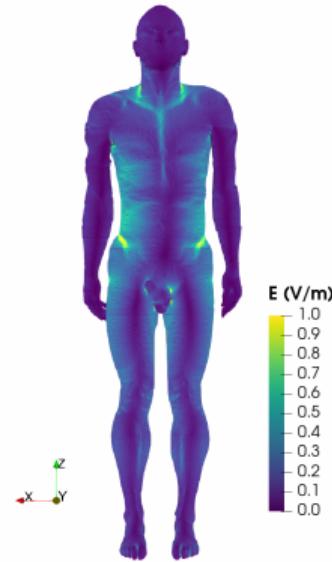
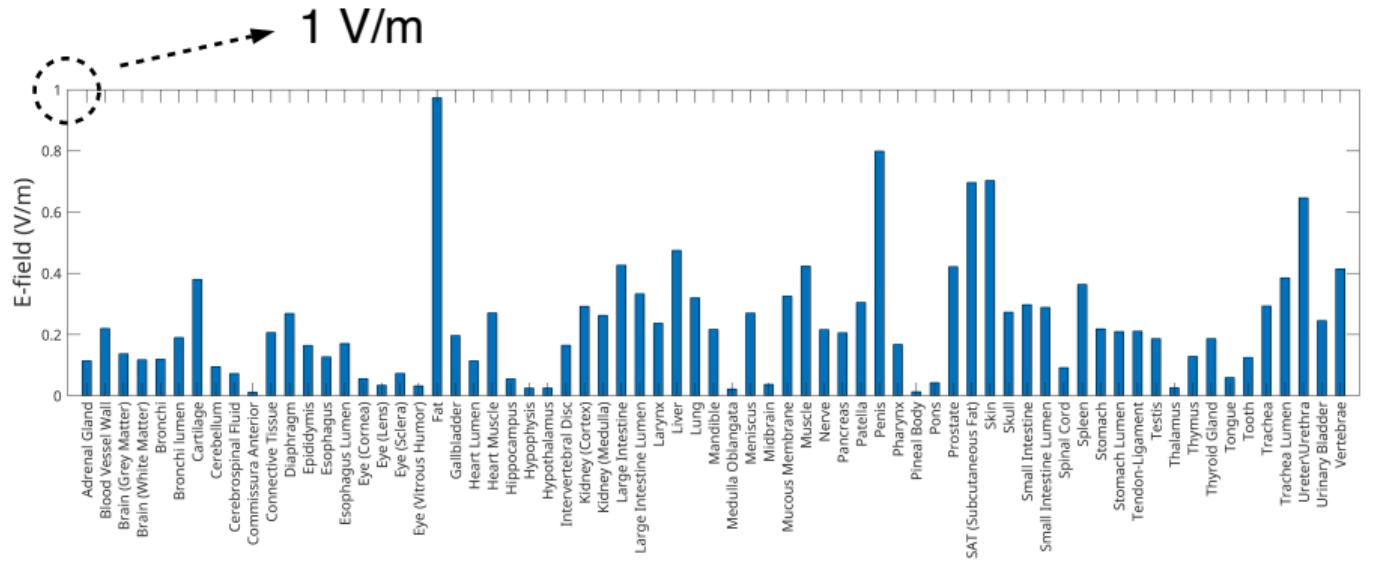
Magnetic flux density vs motion



Case study



Induced electric field

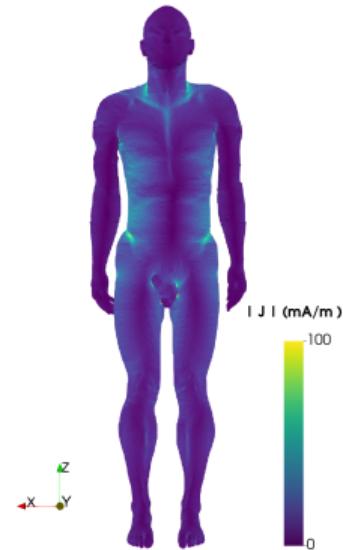
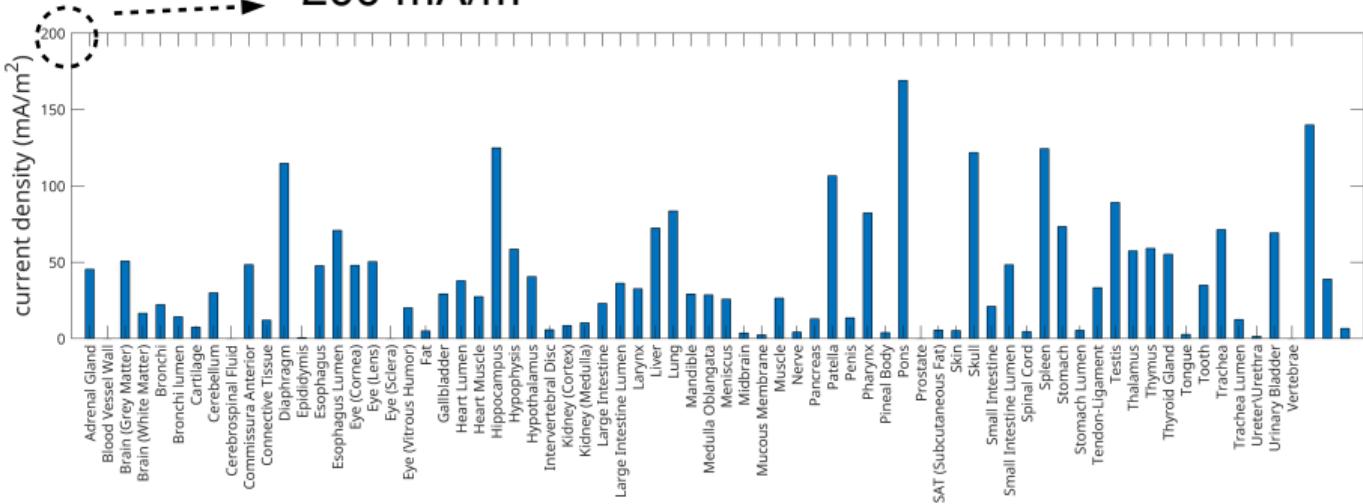


Max exposure in FAT-tissue

about 1 V/m, well below the basic restriction of 11.5 V/m
(ICNIRP guidelines 2010)

Induced current density

200 mA/m²



Max exposure in FAT-tissue
about 169 mA/m², very close to 170 mA/m²
(ICNIRP guidelines 1998)

References I

- [1] A. Canova, F. Freschi, L. Giaccone, and M. Repetto, "Exposure of working population to pulsed magnetic fields," *IEEE Transactions on Magnetics*, vol. 46, pp. 2819–2822, 8 2010.
- [2] A. Canova, F. Freschi, L. Giaccone, and M. Manca, "A simplified procedure for the exposure to the magnetic field produced by resistance spot welding guns," *IEEE Transactions on Magnetics*, vol. 52, 3 2016.
- [3] V. Cirimele, F. Freschi, L. Giaccone, L. Pichon, and M. Repetto, "Human exposure assessment in dynamic inductive power transfer for automotive applications," *IEEE Transactions on Magnetics*, vol. 53, 2017.
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