Occupational exposure to quasi-static electromagnetic fields and the EU 2004/40 Directive: assessment of induced current densities in realistic scenarios using a 3D dosimetric approach based on the scalar potential finite difference numerical technique and a posturable digital body model

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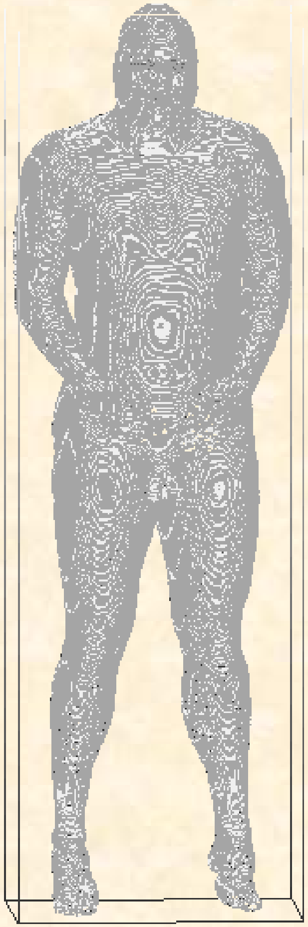
Numerical dosimetry and 2004/40 European Directive

- The endorsement of the 2004/40 European Directive implies that people involved in assessing occupational exposures to electromagnetic fields will necessarily have to deal with electromagnetic dosimetry.
- Numerical techniques are the preferred choice for electromagnetic dosimetry because:
  - measurements are not allowed by the Directive for this purpose;
  - analytical techniques cannot provide the necessary accuracy.
- In this presentation, we will show that currently available methods can provide an efficient and effective way of solving the problem of assessing compliance with the Directive exposure limit values.

Reference voxel phantom: VHP body model

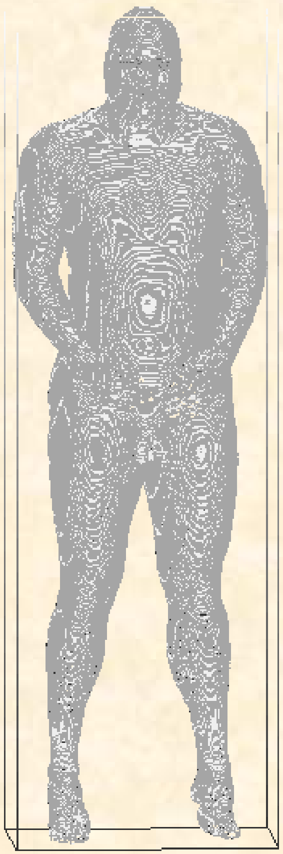


Model	nx	ny	nz	n_cells	Model memory occupation [Mb]
Head 1mm	178	235	211	8826130	8.42
Man 3mm	196	114	626	13987344	13.34
Man 2mm	293	170	939	46771590	44.60
Man 1mm	586	340	1878	374172720	356.84

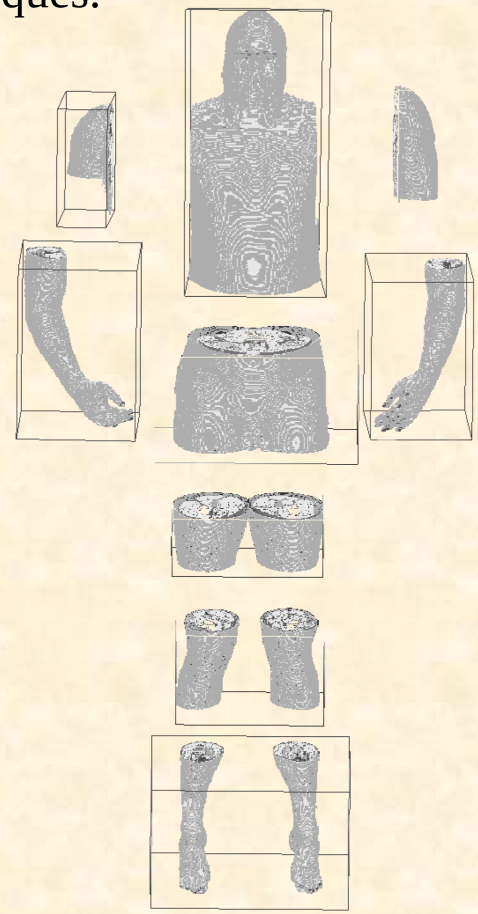
The reference voxel phantom is the VHP model of the entire body at 3mm resolution. With that choice the dosimetric problems can be solved with standard PC. With higher resolutions, problems may arise regarding both calculus time and memory resources demand.

Articulation algorithm: subdivision in portions

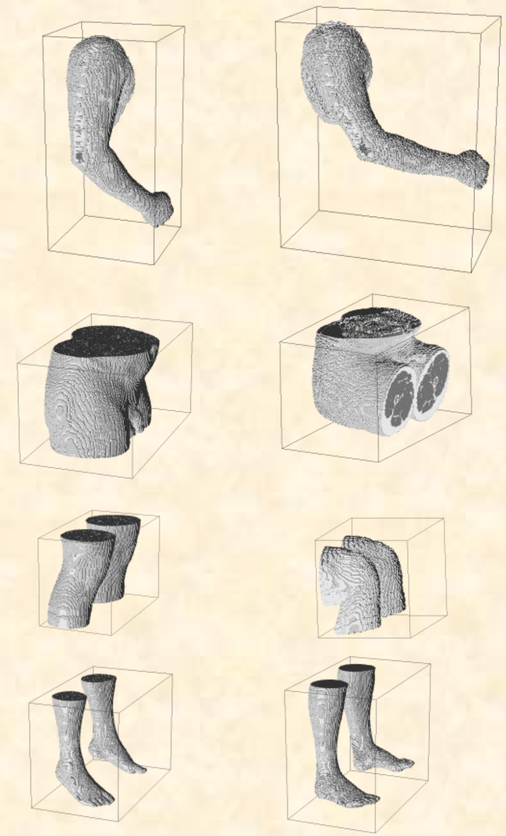
Vhp models represent the human body in standing posture and cannot be directly used for dosimetric evaluations in different postures, as required by occupational exposure studies. An articulation algorithm is presented that is particularly suited for use in conjunction with finite difference calculus techniques.



Model at rest

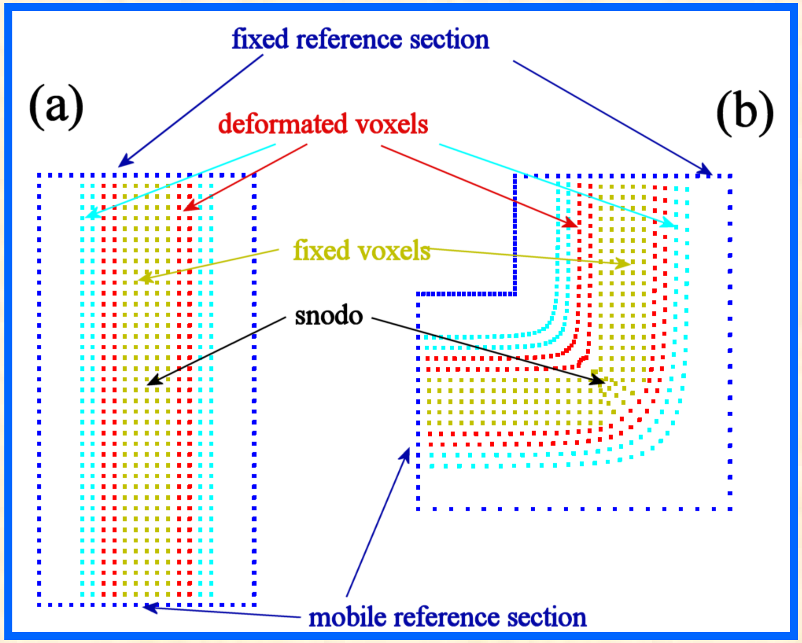


Subdivision in portions



Articulation of the single portions

Elastic model



An elastic model is built which separates voxels that undergo rigid translations and rotations (bones for example) and voxels that go through elastic deformations (fleshy parts).

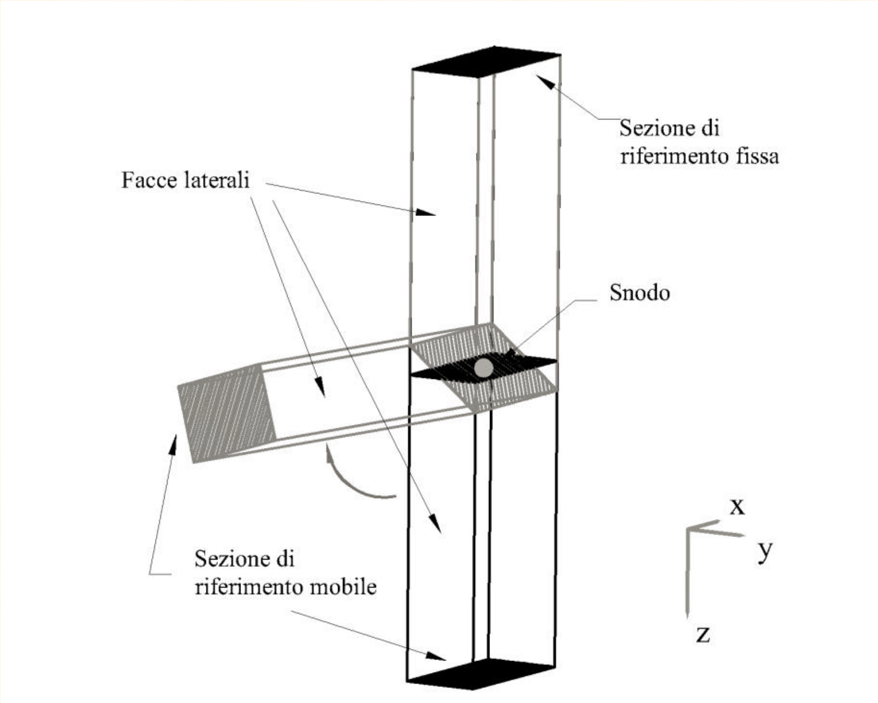
The articulation process deforms the voxels close to the joints, so that the articulated body model has to be **resampled** over a regular grid before it can be used as a base for finite difference calculations.

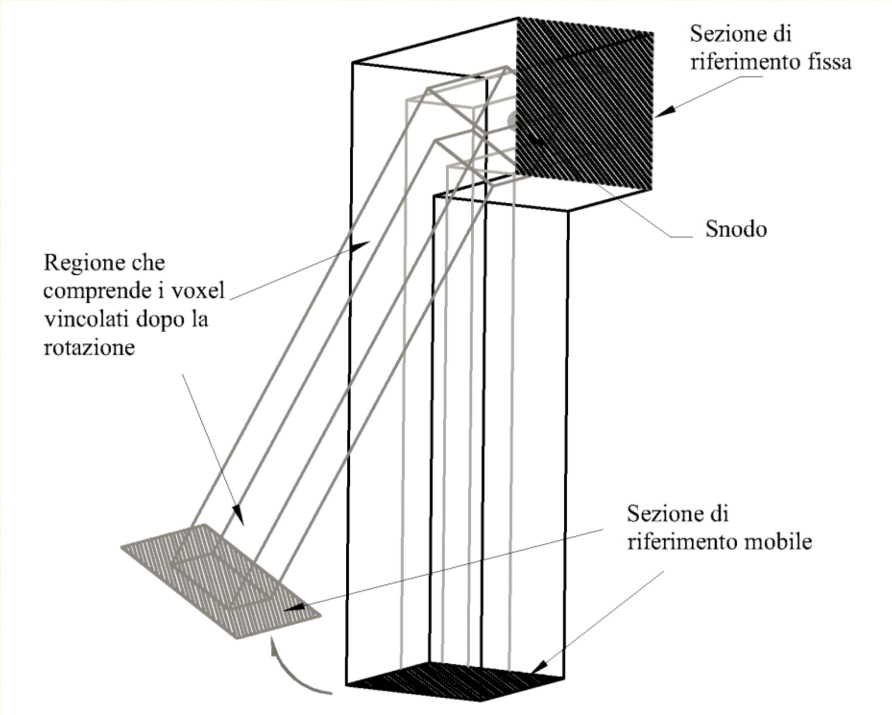
Resampling in two steps

Schematic models

Schematic model of knee articulation

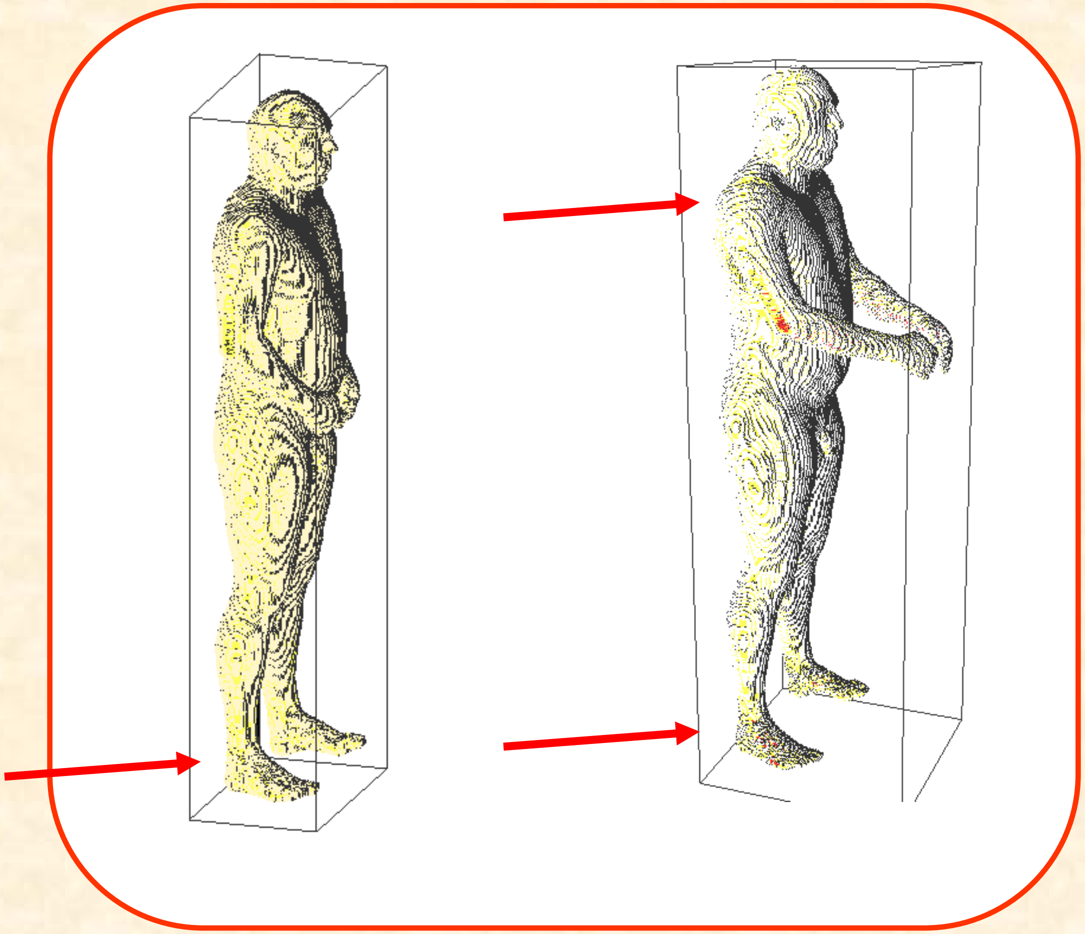
Schematic model of shoulder articulation

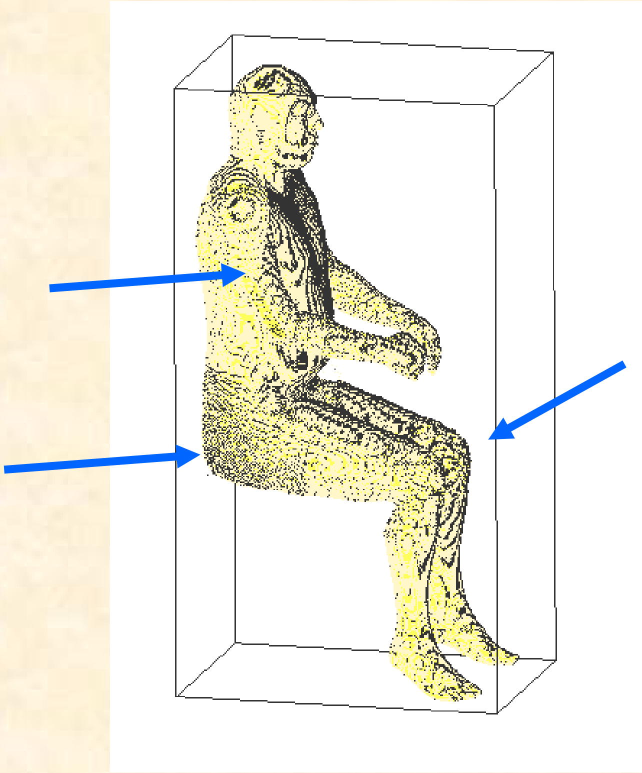




Articulated voxel phantoms

The articulated portions are re-assembled together with the others (translated and/or rotated) to compose the articulated voxel phantom

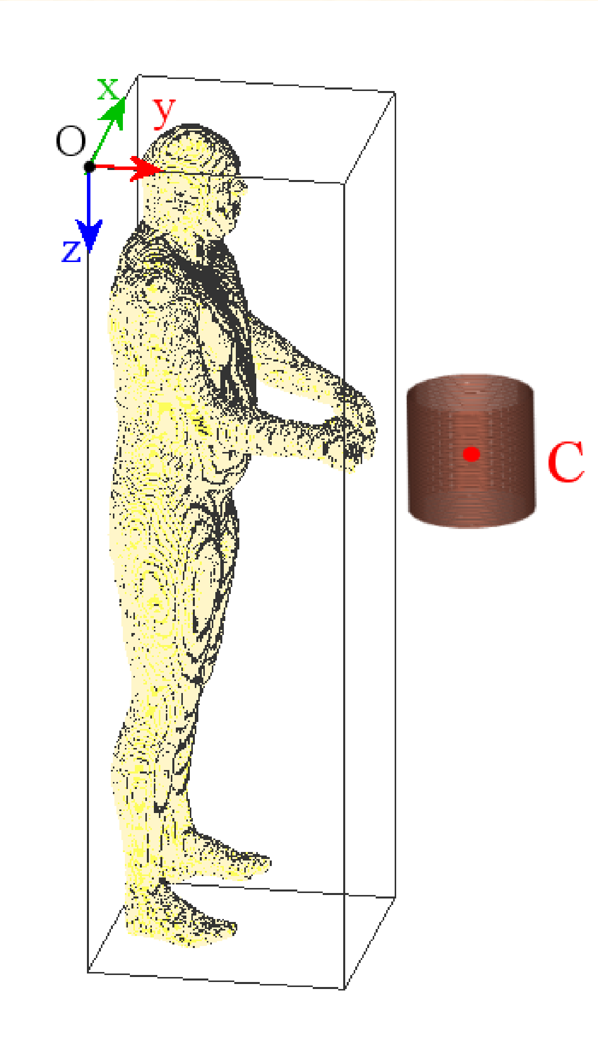




Models used in the examples showed in this presentation

Case 1

Case 1: induction heater



- Used in the gold industry
- **Magnetic field only**
- F = 3450 Hz
- I = 400 A
- Monophase source

- Cx=0,3m Cy=0,75m Cz=0,75m
- Radius= 0,09m
- The edge of the fingers are less then 10 cm distant from the conductors

Case 1: induction heater, B field

Field distribution in the body model volume

σ

SPFD

$$\Phi_{n0} = \left(\frac{1}{\sum_{i=1}^{6} \bar{\sigma}_{mi}} \right) \cdot \sum_{i=1}^{6} \left\{ \bar{\sigma}_{mi} \left[\Phi_{ni} - (-1)^{i} j\omega l_c A_{mi} \right] \right\}$$

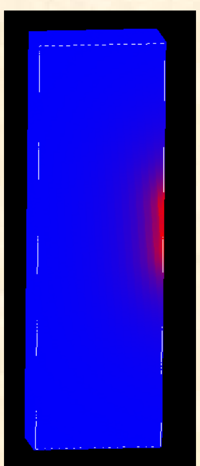
Post processing

$$J_{x0} = -\sigma_0 \cdot \left(\frac{\Phi_1 - \Phi_0}{l_c} + j\omega \vec{A}_{m1} \right)$$

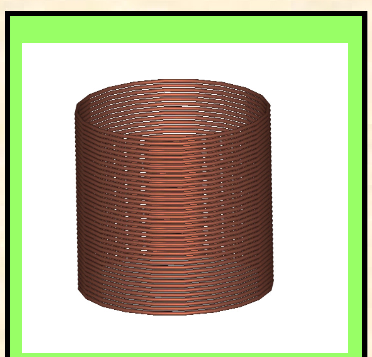
$$J_{y0} = -\sigma_0 \cdot \left(\frac{\Phi_3 - \Phi_0}{l_c} + j\omega \vec{A}_{m3} \right)$$

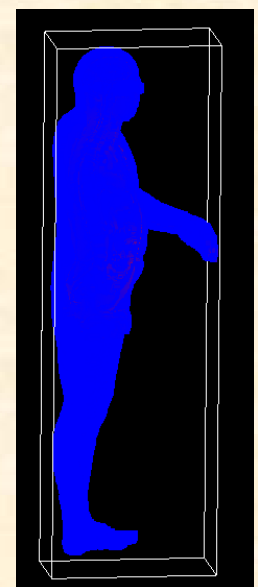
$$J_{z0} = -\sigma_0 \cdot \left(\frac{\Phi_5 - \Phi_0}{l_c} + j\omega \vec{A}_{m5} \right)$$

$\vec{A}$



Coil model





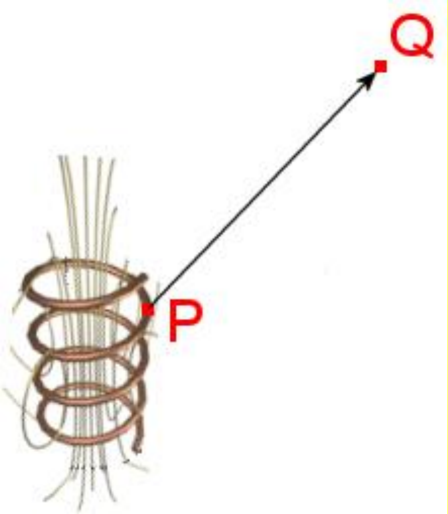
$\left| \vec{J} \right|$

Case 1: induction heater
Modeling the source

- Based on the numerical integration of Laplace law
- Solenoid dimensions (diameter, length) are taken from manufacturer's specifications
- Coil current is in agreement with manufacturer's electrical data (voltage, power)
- Current x turn product and coil exact position in the apparatus are adjusted to fit experimental data

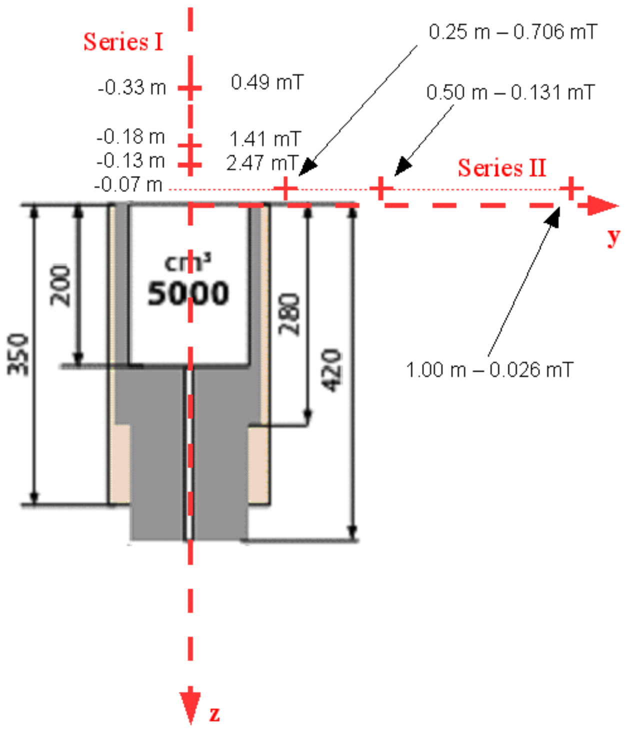
Here I is the coil current, Q is the point where fields are computed, Γ is the coil path and P is a generic point along it

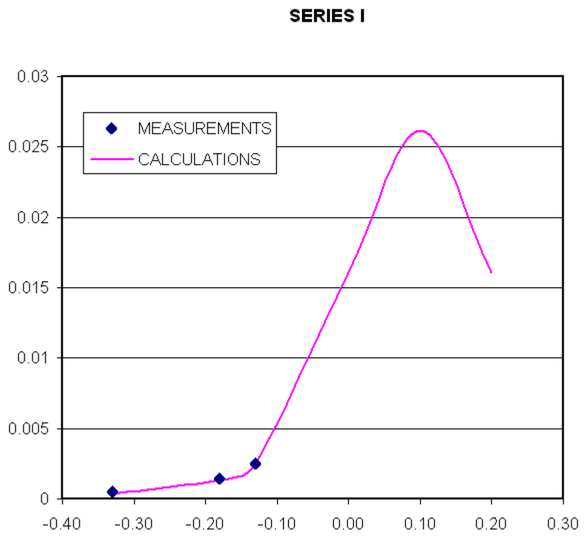
$$\mathbf{B}\;Q\;=\frac{\mu_0\, I}{4\pi}\int_{P\in\Gamma}\frac{\mathbf{dP}\times\;\;\mathbf{Q}-\mathbf{P}}{\left|\mathbf{Q}-\mathbf{P}\right|^3}\qquad\qquad \mathbf{A}\;Q\;=\frac{\mu_0\, I}{4\pi}\int_{P\in\Gamma}\frac{\mathbf{dP}}{\left|\mathbf{Q}-\mathbf{P}\right|}$$

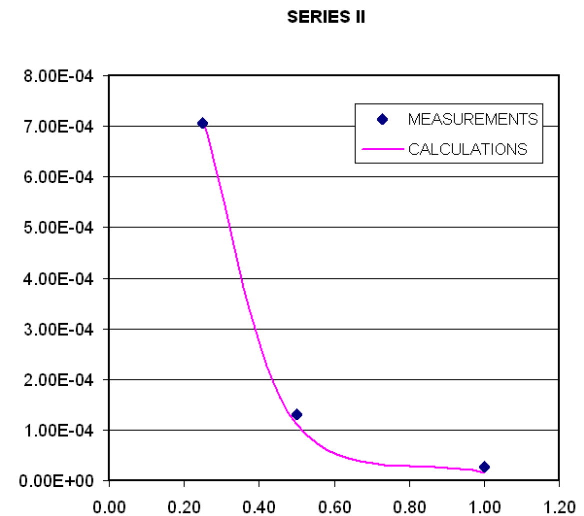


Case 1: induction heater
Modeling the source (cont.)

Measurement setup and results





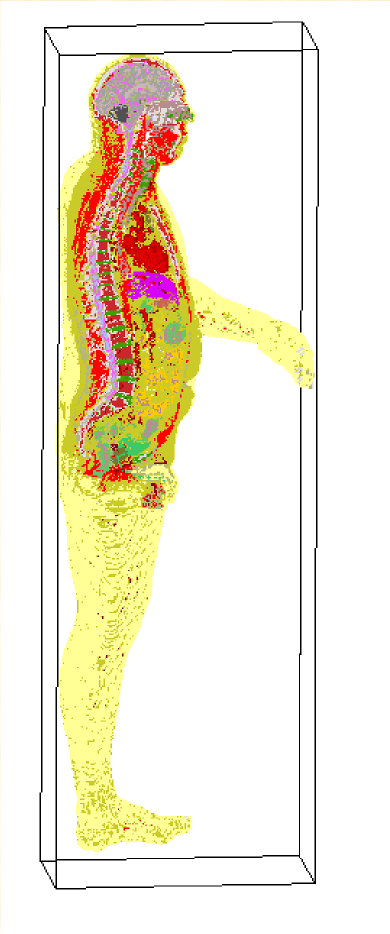


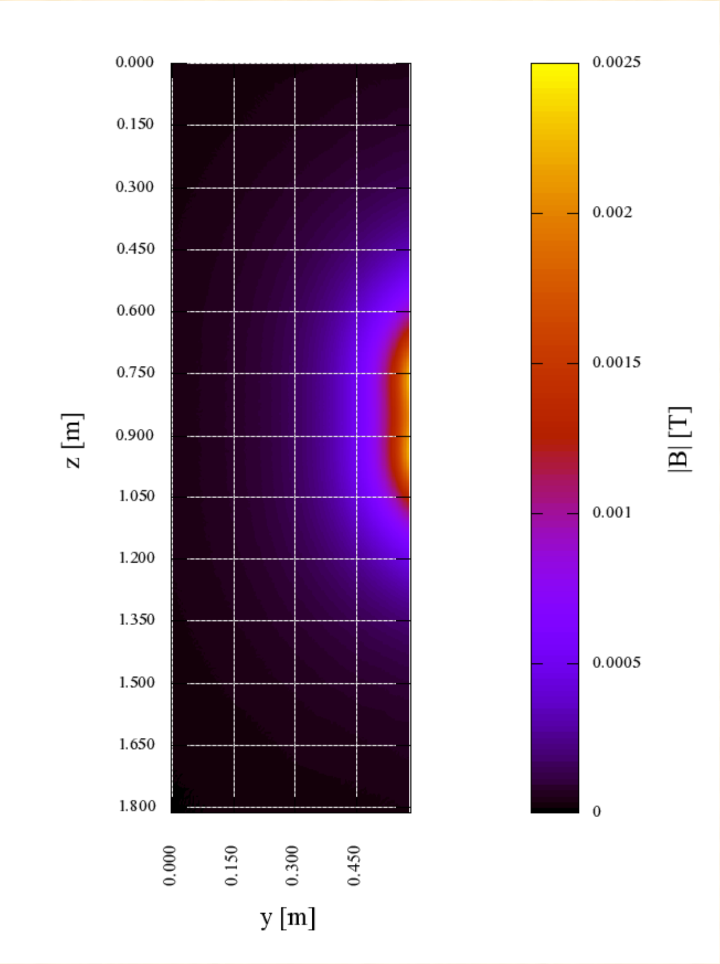
Case 1: induction heater B field

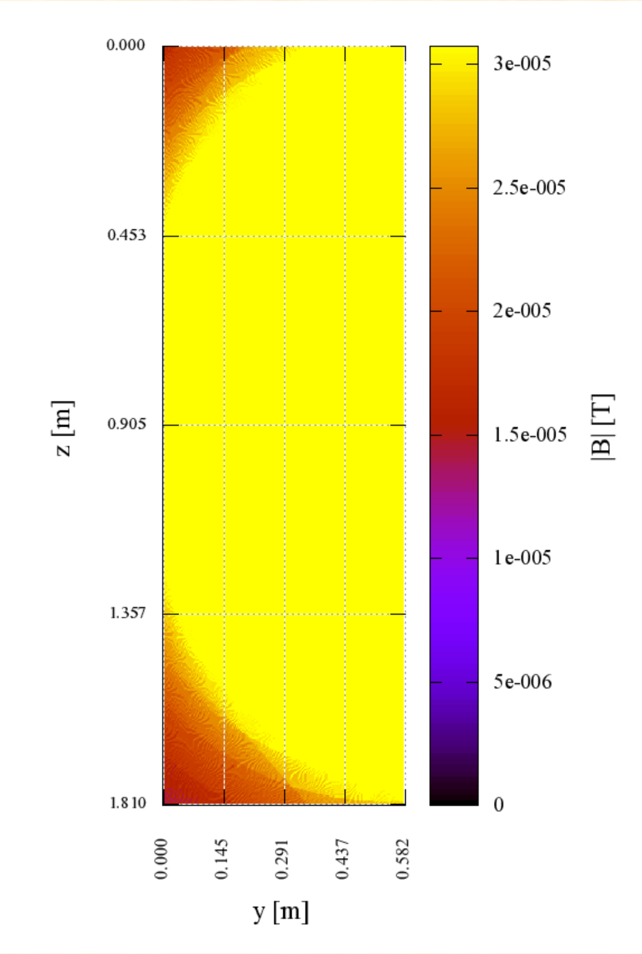
Median sagittal section *(x=0,3 m)*

The maximum value (close to the hands ant to the coils) is over 2,5 mT

The major part of the body volume is over the action value 30,7 μT



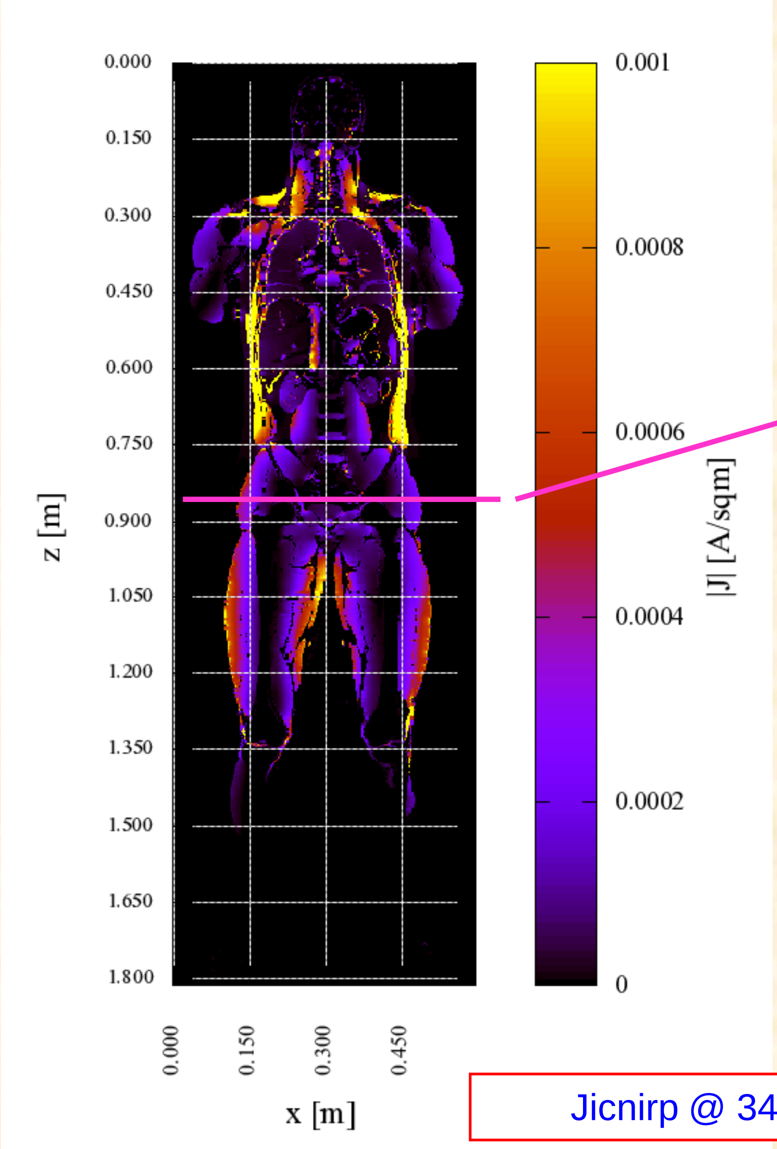




Case 1: induction heater J

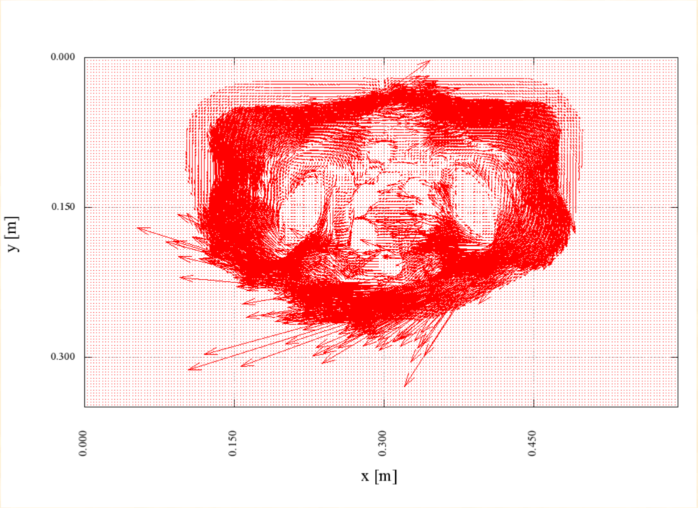
Coronal section

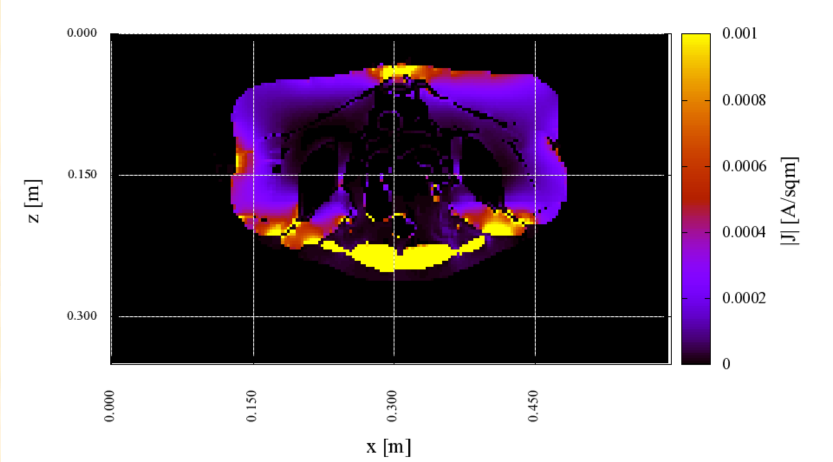
(y=0,15 m)



Axial section

(z=0,85 m)





Jicnirp @ 3450 Hz = 0,0345 A/sqm

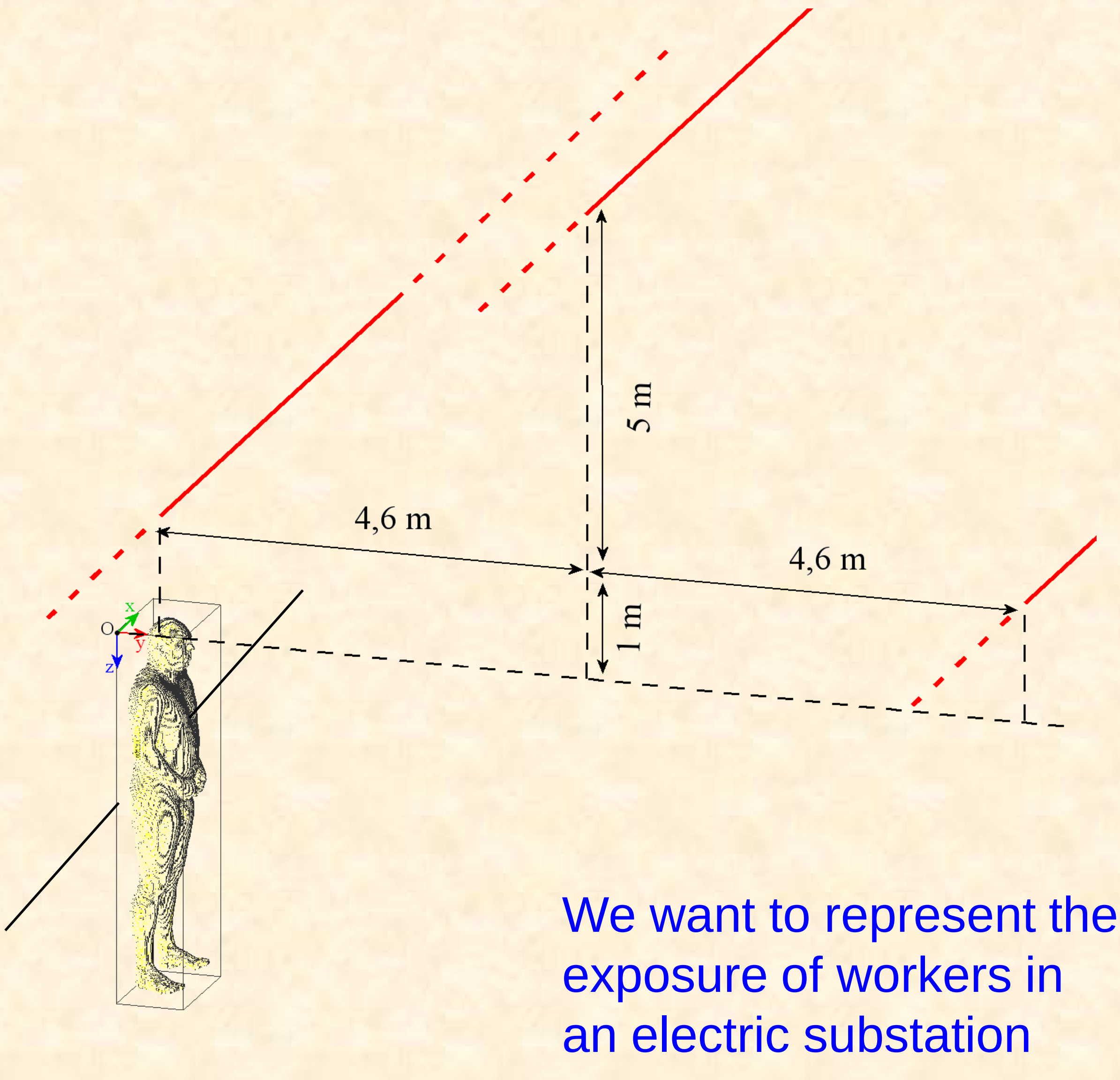
Case 1: induction heater

Parts of the body in which the exposure limit value of the directive 34,5 mA/sqm is exceeded.

	|J| max [mA/sqm]
Bladder	40
Hands (Cartillage)	111
Hands (Bone)	95
CerebroSpinalFluid	113
Colon	108
Arms (Muscle)	235
Pancreas	51
Small Intestine	202
GallBladder	142
Stomach	95

Case 2

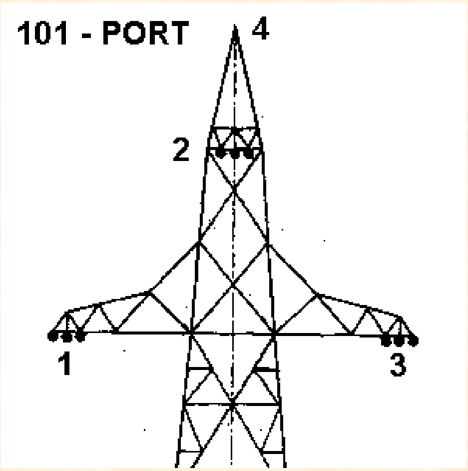
Case 2: power line



We want to represent the exposure of workers in an electric substation

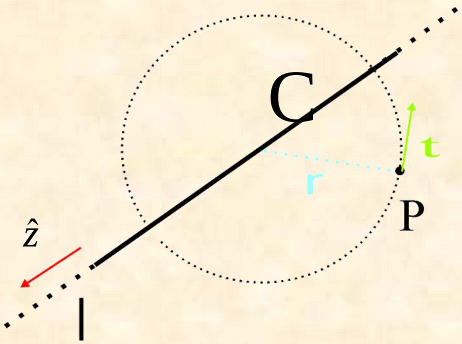
- **Magnetic field only**
- F = 50 Hz
- |I| = 2955 A
- |Vgr|= $\frac{380000}{\sqrt{3}} = 219393$ V
- Balanced three-phase source

The closer conductor is 1 meter above the head.

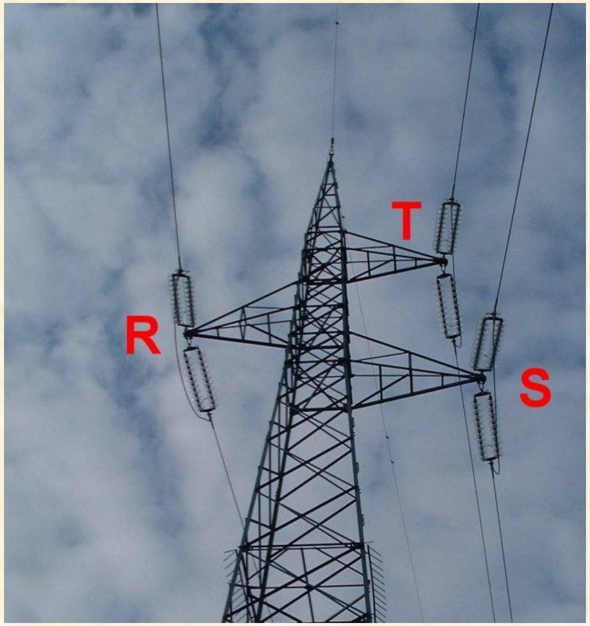


Case 2: power line, Modeling the source

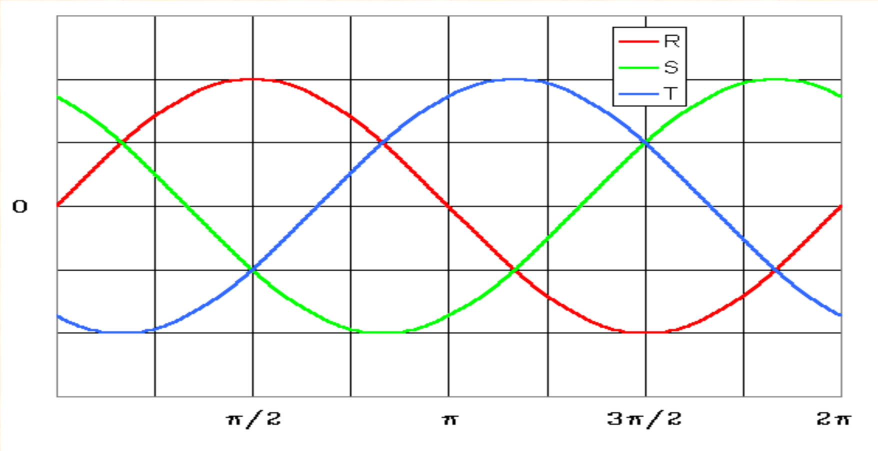
For each conductor, the Biot Savart law is used



$$\vec{B}(P) = \frac{\mu \cdot I}{2\pi} \cdot \frac{\hat{z} \times \vec{r}}{r^2} = \frac{\mu \cdot I}{2\pi \cdot r} \cdot \hat{t}$$



There is a phase delay of 1/3 of the period (T=0,02 s @ 50 Hz) between the currents on the different conductors.



$$V_R = V_0 \cos \omega t \ , \qquad I_R = I_0 \cos \omega t$$

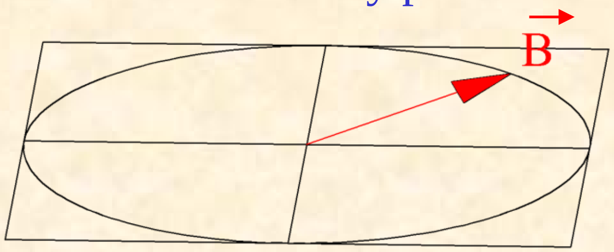
$$V_S = V_0 \cos\left(\omega t + \frac{2\pi}{3}\right) \qquad I_S = I_0 \cos\left(\omega t + \frac{2\pi}{3}\right)$$

$$V_T = V_0 \cos\left(\omega t - \frac{2\pi}{3}\right) \qquad I_T = I_0 \cos\left(\omega t - \frac{2\pi}{3}\right)$$

$$V_R + V_S + V_T = 0 \qquad I_R + I_S + I_T = 0$$

Case 2: power line three-phase impressed fields

The magnetic field generated by a three-phase source is a rotating vector. As time changes, its edge moves on the so called *polarization ellipse*. The edge of the vector makes 1 round every period.



That field can be represented by a complex vector

$$\vec{B}_c = \vec{B}_p + j\,\vec{B}_q$$

Since the SPFD equation has real coefficients, the excitation due to the in-phase and quadrature components of the source can be computed separately. The resulting solutions can then be combined at the post-processing stage to yield the complex induced field

$$\vec{A} = \vec{A}_p + j\vec{A}_q$$

SPFD

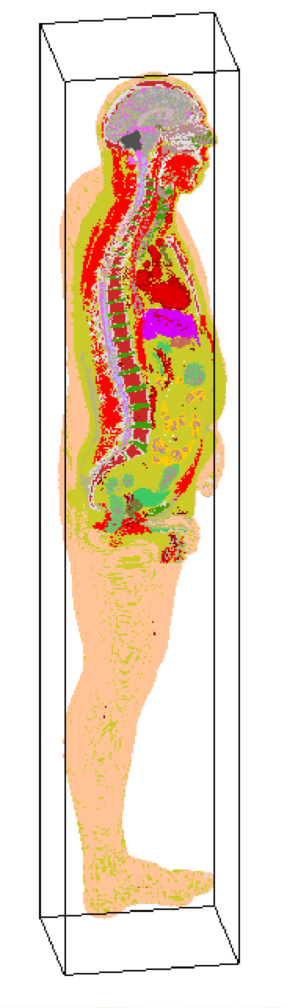
SPFD

$$\Phi^* = \Phi^*{}_p + j\,\Phi^*{}_q$$

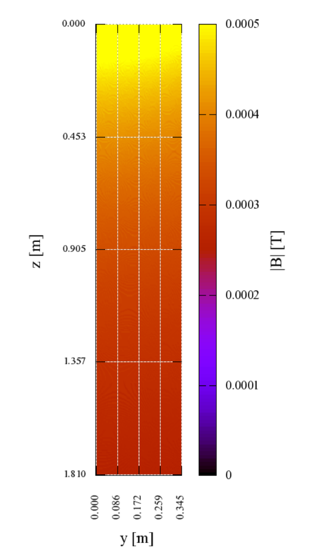
$$\boxed{\vec{J} = \vec{J}_p + j\,\vec{J}_q}$$

Case 2: power line, B field

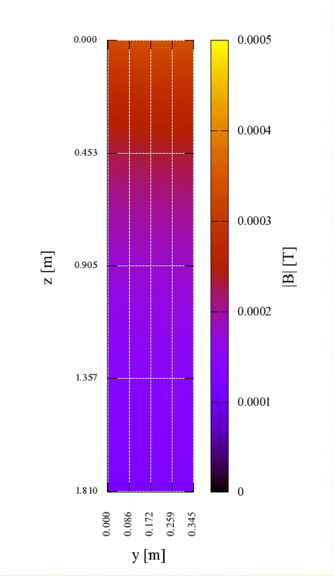
Median sagittal section
(x=0,3 m)



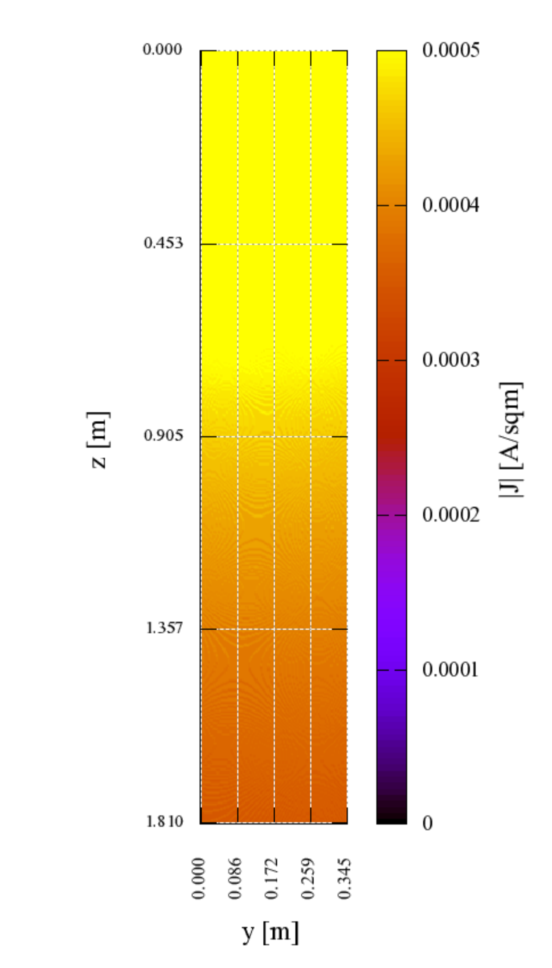
$$\left|\vec{B}_p\right|$$



$$\left|\vec{B}_q\right|$$



$$\left|\vec{B}_r + j\,\vec{B}_q\right|$$

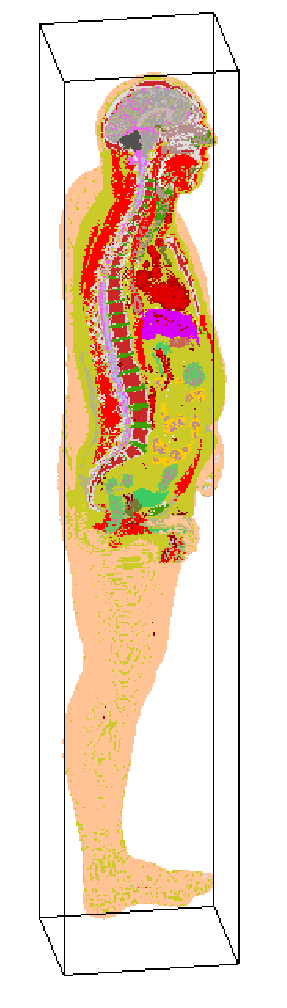


The upper part of the body volume is over the action value 500 μT

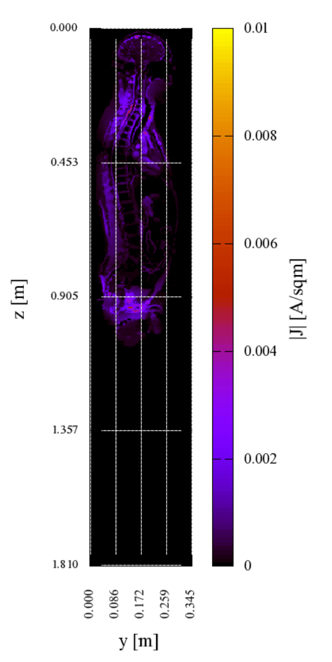
Case 2: power line, B, Jp & Jq

Median sagittal section

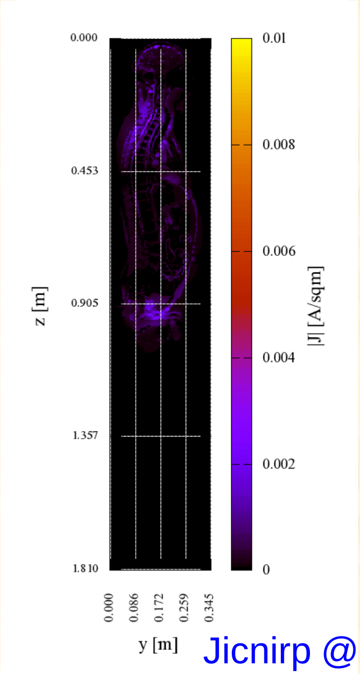
(x=0,3 m)



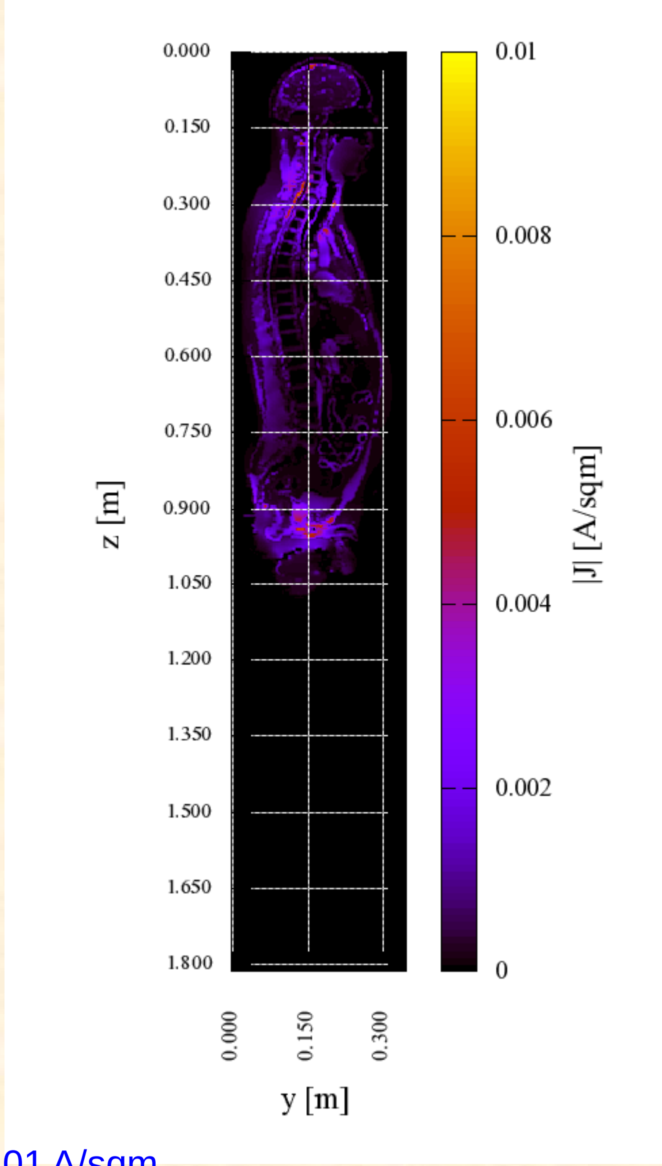
$$\left|\vec{J}_p\right|$$



$$\left|\vec{J}_q\right|$$

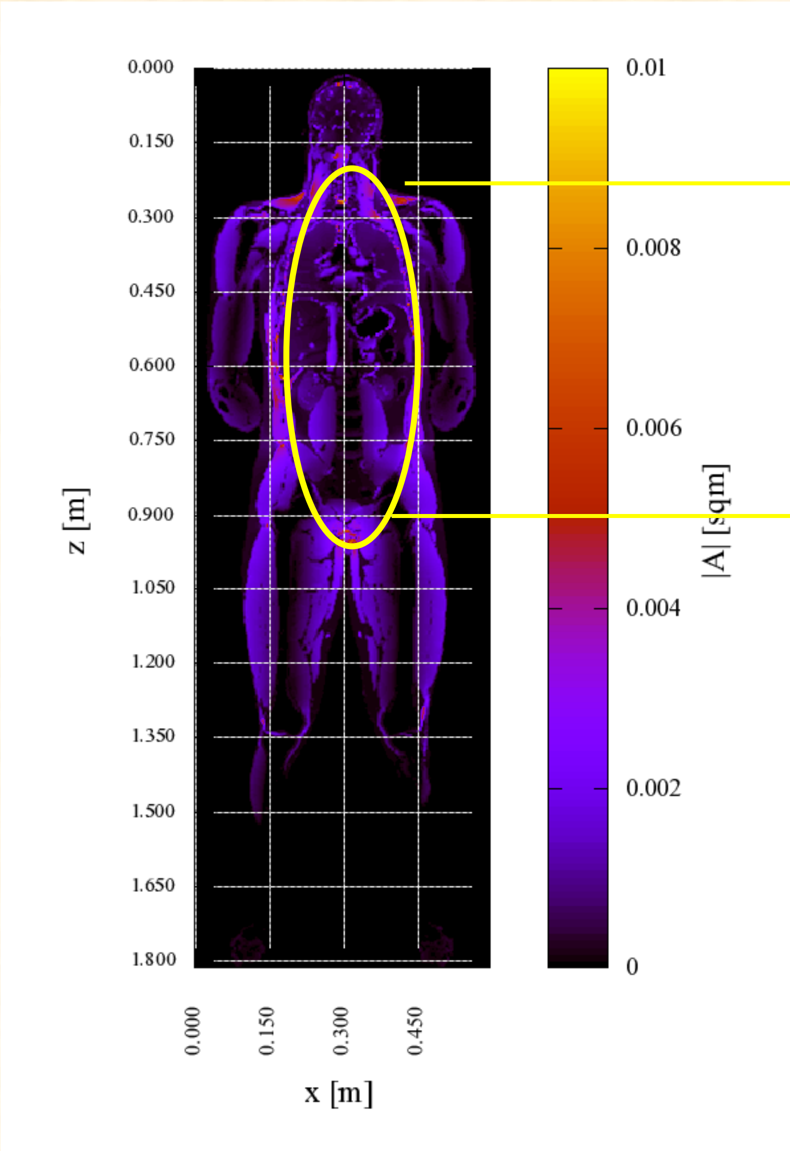


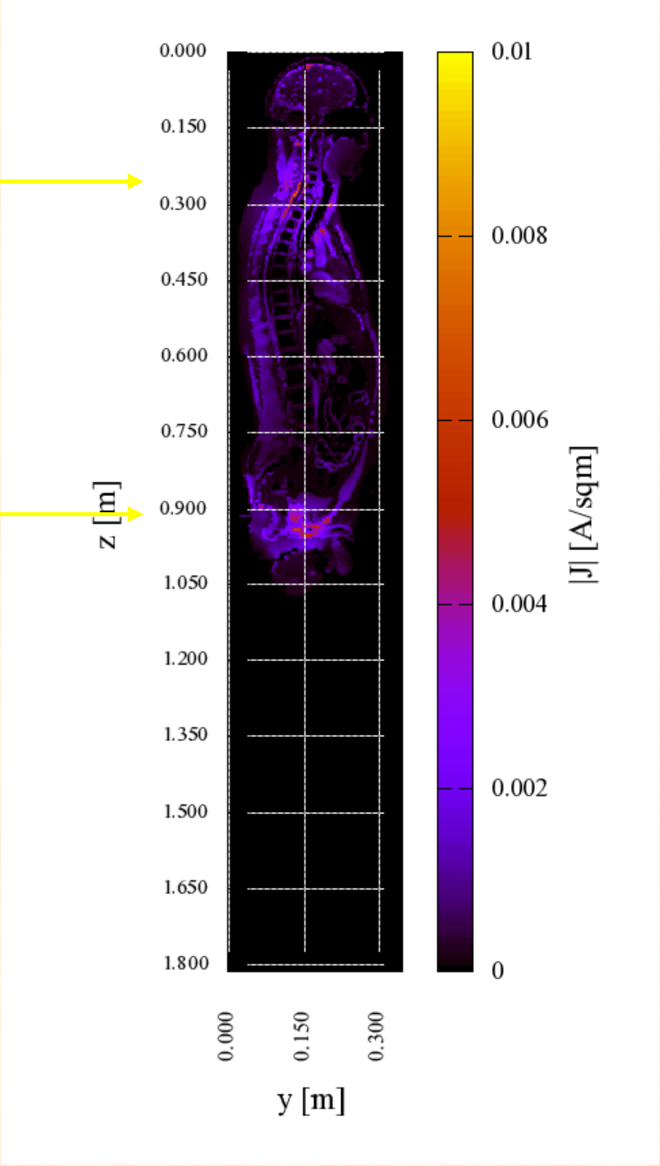
$$\left|\vec{J}_p + j\,\vec{J}_q\right|$$



Jicnirp @ 50 Hz = 0,01 A/sqm

Case 2: power line, B, Jc





Case 2: power line, B, Jc

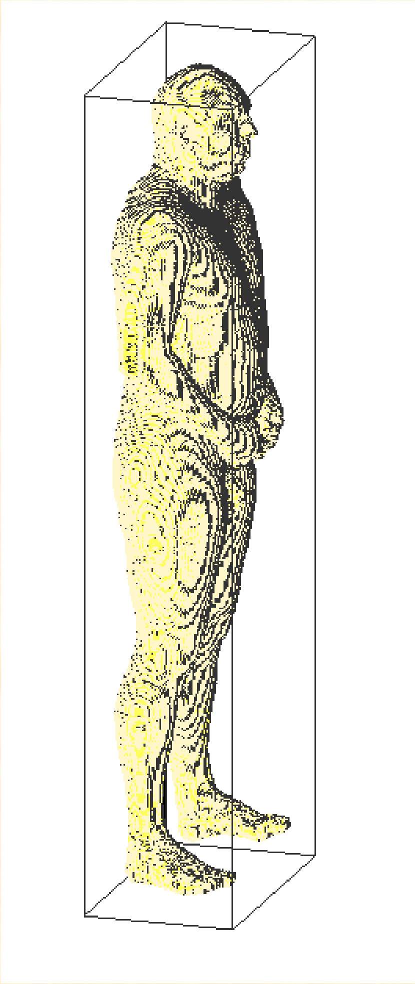
Jicnirp @ 50 Hz =10 mA/sqm

	|J| [mA/sqm]
CerebroSpinalFluid	17,6
Muscle (trunk)	18,9
SmallIntestine	15,8
Stomach	13,9

Exposure to electric field

Case 2: power line, E field

At low frequencies the body tissues behave like good conductors. That propriety allows to split the problem in **two parts**.

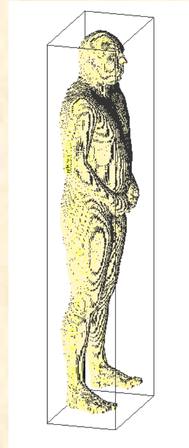


The **external problem** search for the time varying surface charge induced electro-statically by the source field.

The **internal problem** is similar to the magnetic one, with the difference that the excitation is no more represented by a magnetic vector potential but by the surface charge calculated solving the external problem.

Case 2: power line, E field

Φ_{body}= constant



LAPLACE Eq.

$$\nabla^2\Phi = 0$$

σ

SPFD

$$\Phi_{n0} = \left(\frac{1}{\sum_{i=1}^{6}\bar{\sigma}_{mi}}\right)\cdot\left[\sum_{i=1}^{6}\left(\bar{\sigma}_{mi}\cdot\Phi_{ni}\right)+\frac{j\omega q_{n0}}{l_c}\right]$$

$\Phi_{borders}$= $\Phi_{sources}$

Post processing

$$\oint\!\!\!\oint_S \varepsilon_0 \left(-\nabla\Phi\right)\cdot d\vec{S} = q$$

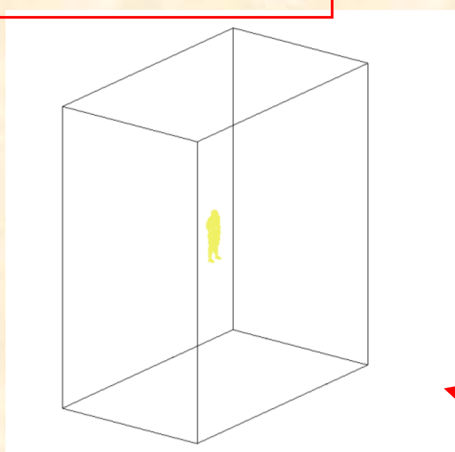
q

Post processing

$$J_{x0} = -\sigma_0\cdot\left(\frac{\Phi_1-\Phi_0}{l_c}\right)$$

$$J_{y0} = -\sigma_0\cdot\left(\frac{\Phi_3-\Phi_0}{l_c}\right)$$

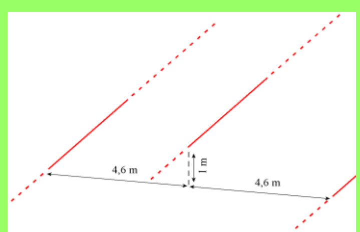
$$J_{z0} = -\sigma_0\cdot\left(\frac{\Phi_5-\Phi_0}{l_c}\right)$$



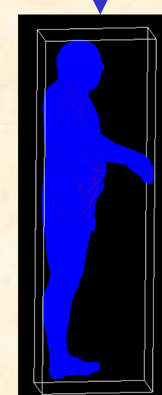
Electrostatic potential distribution on the borders of a volume much greater then the phantom volume

Φ

Power line model



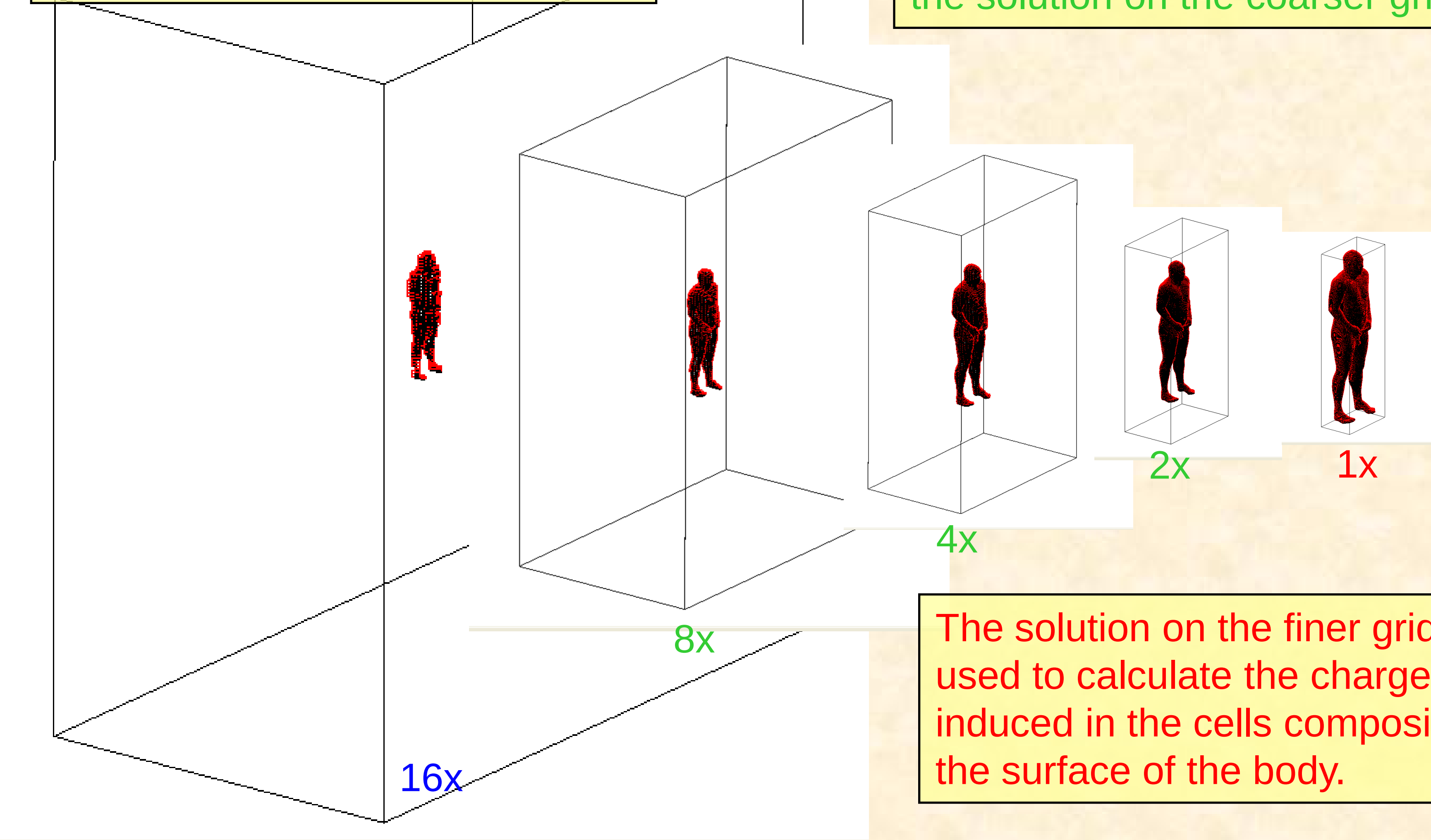
$\left|\vec{J}\right|$



Case 2: power line, external problem

On the borders of the bigger volume, at the first step, it can be assumed that the potential is not perturbed by the voxel phantom

At each intermediate step the potential distribution on the border is obtained interpolating the solution on the coarser grid

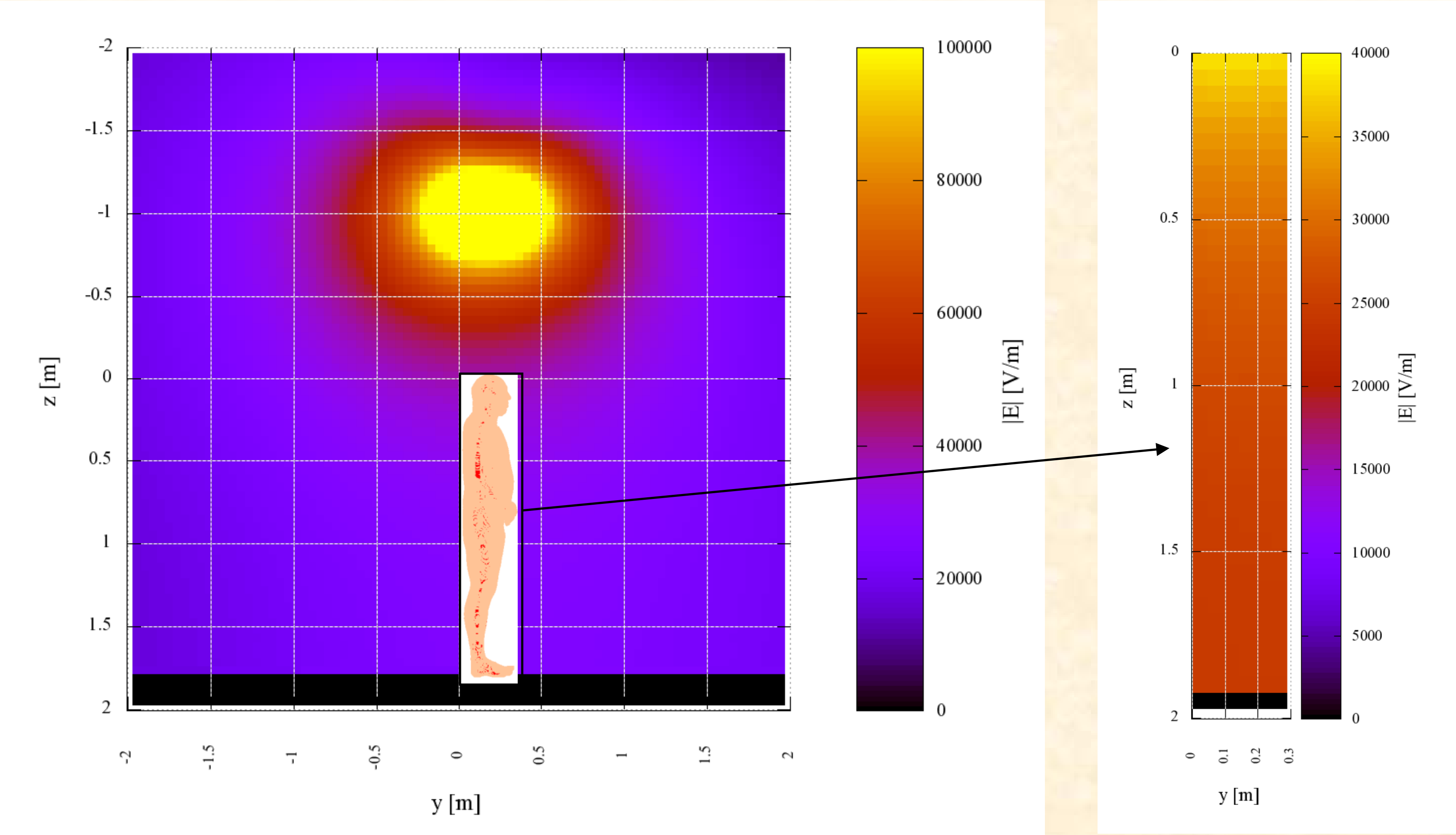


The solution on the finer grid is used to calculate the charge induced in the cells composing the surface of the body.

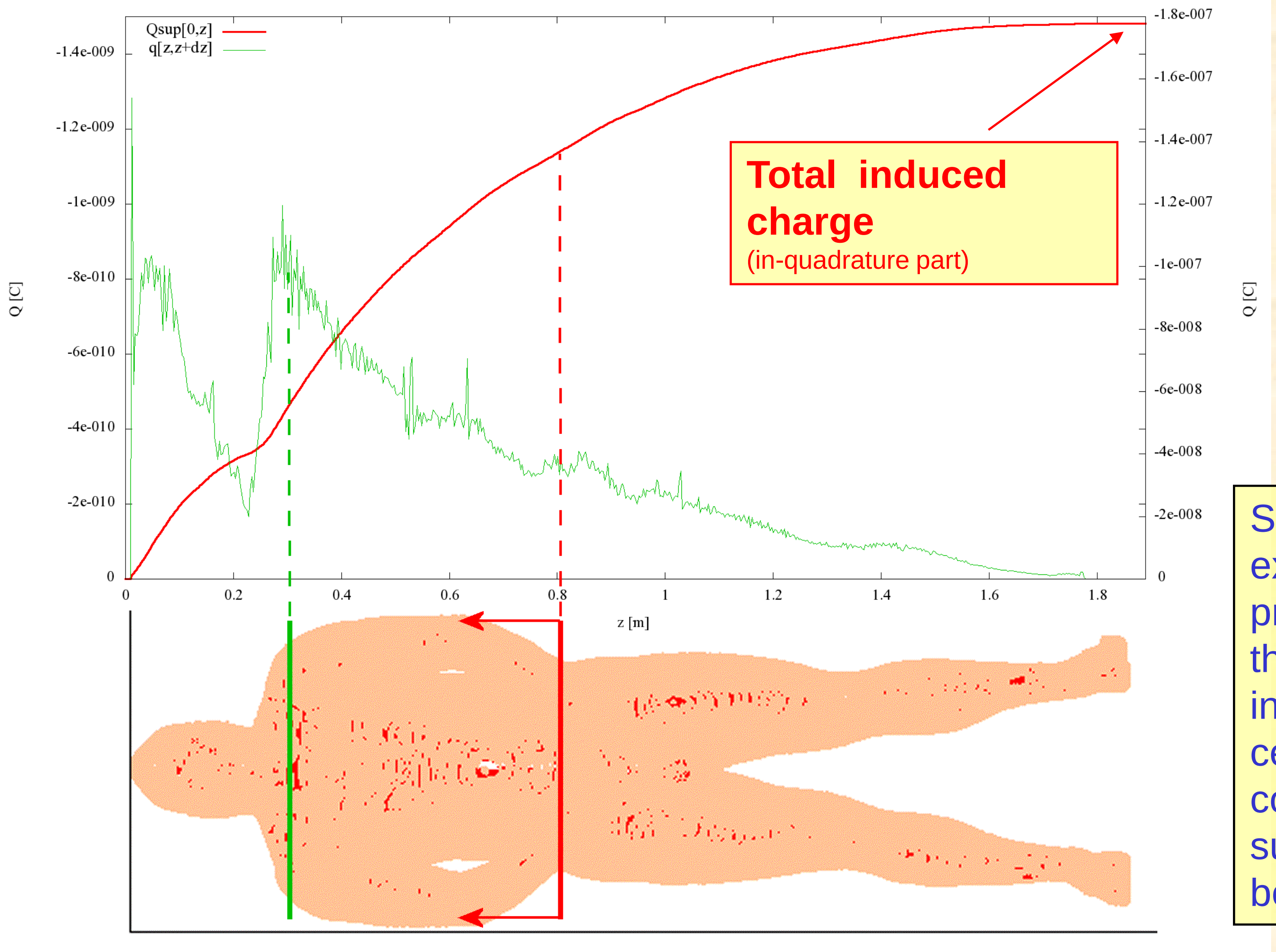
Case 2: power line, E field

$$\left|\vec{E}_p + j\,\vec{E}_q\right|$$

The entire body volume is over the action value 10kV/m



External problem: grounded case

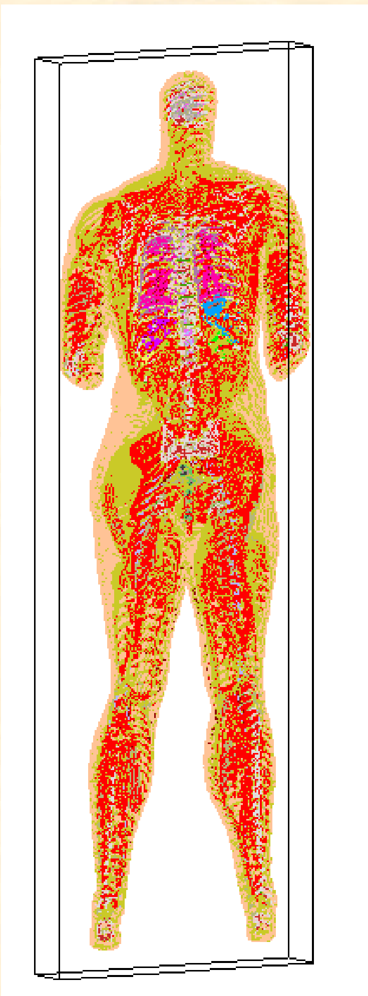


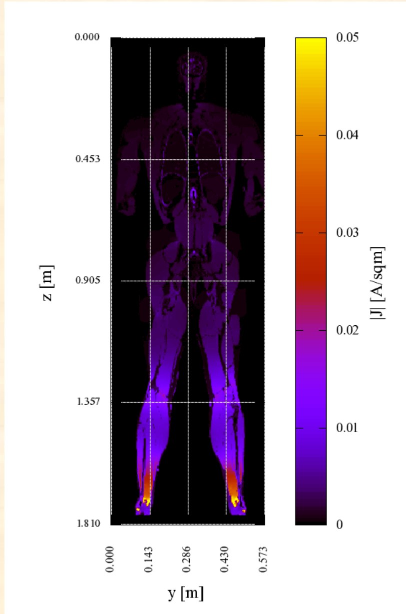
Solving the external problem gives the charge induced in the cells composing the surface of the body.

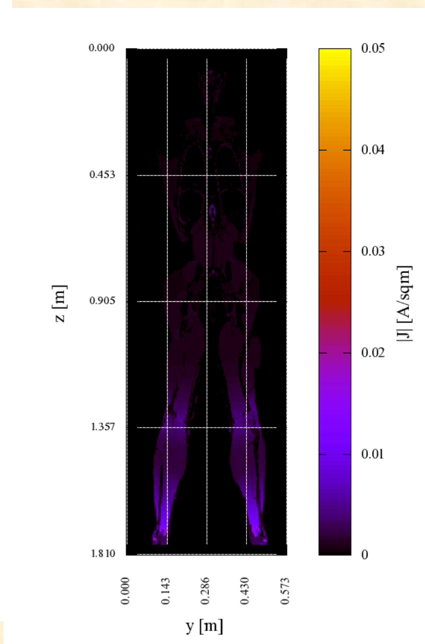
Internal problem: grounded case

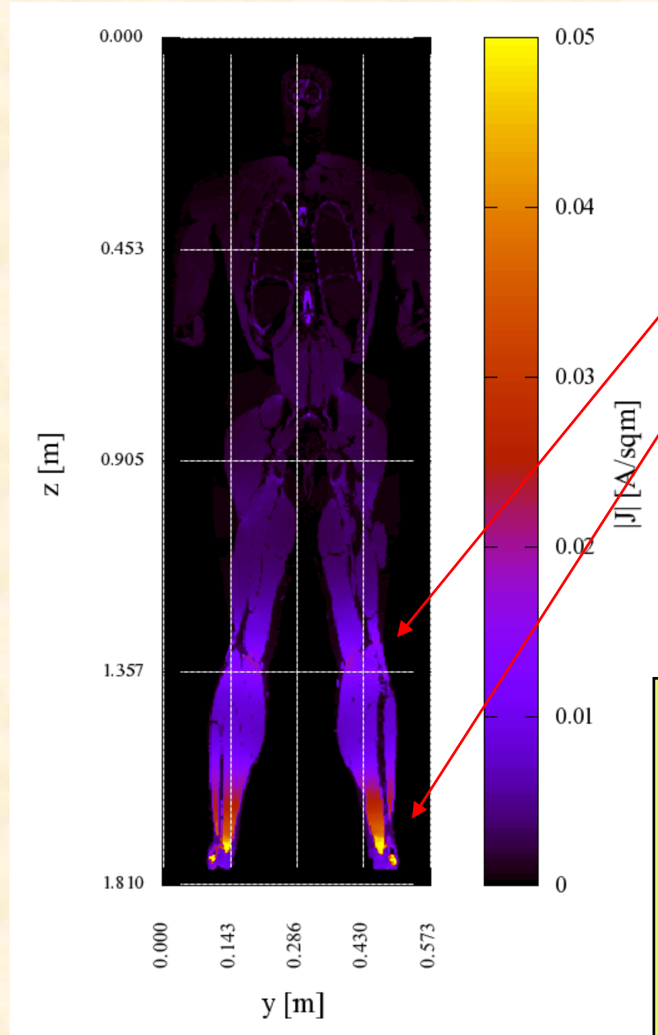
Coronal section

(x=0,10 m)









The current density is more intense where the section of the body perpendicular to the current flow is narrower.

The rate of convergence is much slower then in the magnetic field exposure case.

Jicnirp @ 50 Hz = 0,01 A/sqm

Case 2: power line, E

Jicnirp @ 50 Hz =10 mA/sqm

	|J| [mA/sqm]
Ankles (bone)	90,7
Foot (cartilage)	95,6
CerebroSpinalFluid	42,6
GallBladderBile	13,3
Legs (Muscle)	144,0
Legs (Nerve)	18,6
Pancreas	11,7
SmallIntestine	16,1
Stomach	17,7

Composition ?

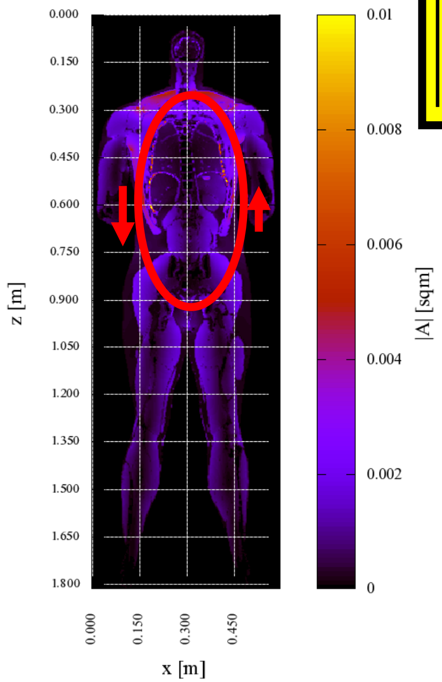
- ICNIRP guidelines tell to consider *separately* the effects of electric and magnetic field.
- Phase delay between voltage and current on conductors of very high voltage power lines is generally known.
- If the right phase is assigned to voltage and current on conductors during the resolution of the dosimetric problem, at the end the currents induced by electric and magnetic field can be composed:

$$\vec{J}_B = \vec{J}_{p\vec{B}} + j\,\vec{J}_{q\vec{B}}$$

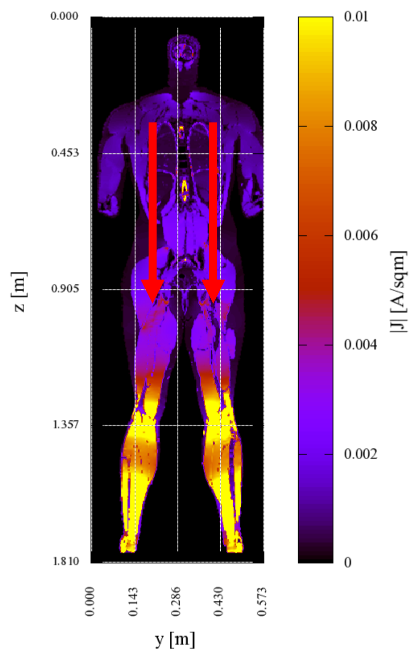
$$\vec{J}_E = \vec{J}_{p\vec{E}} + j\,\vec{J}_{q\vec{E}}$$

$$\vec{J}_{B+E} = \left(\vec{J}_{p\vec{B}} + \vec{J}_{p\vec{E}}\right) + j\left(\vec{J}_{q\vec{B}} + \vec{J}_{q\vec{E}}\right)$$

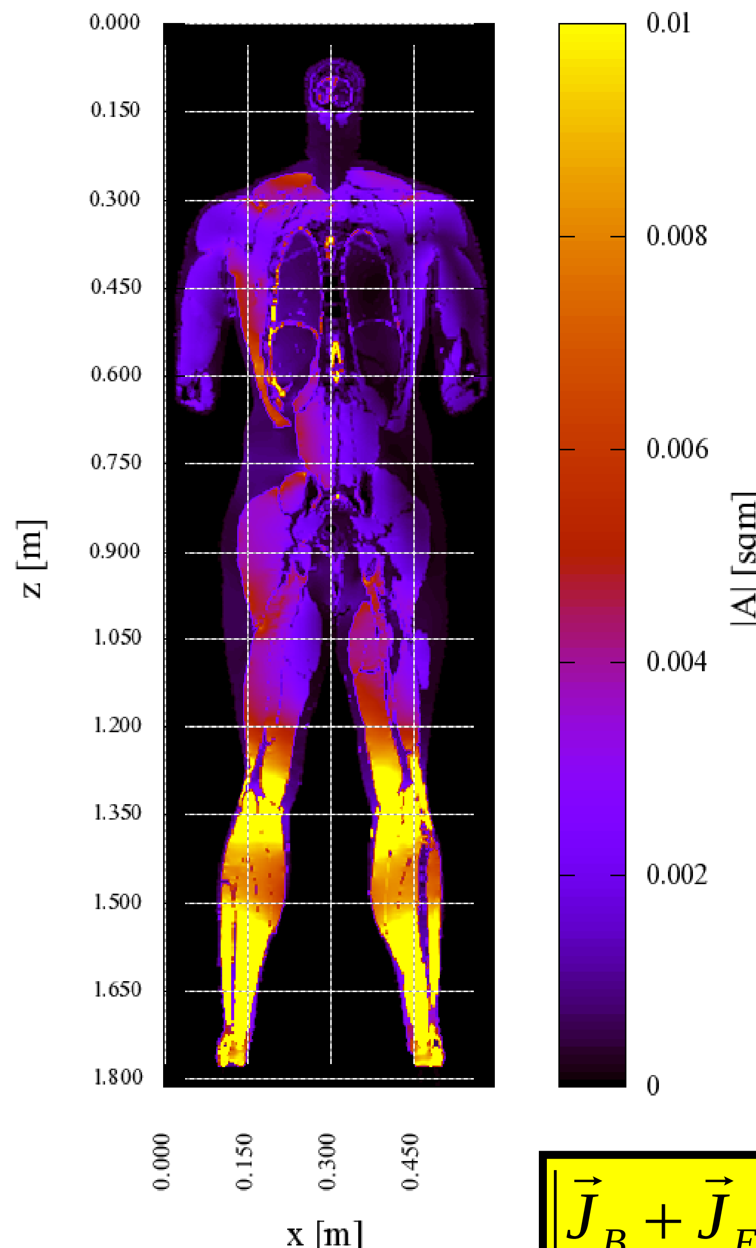
- The following slides refer to the case in which voltage and current on each conductor are in phase (resistive load).



$\left|\vec{J}_B\right|$



$\left|\vec{J}_E\right|$



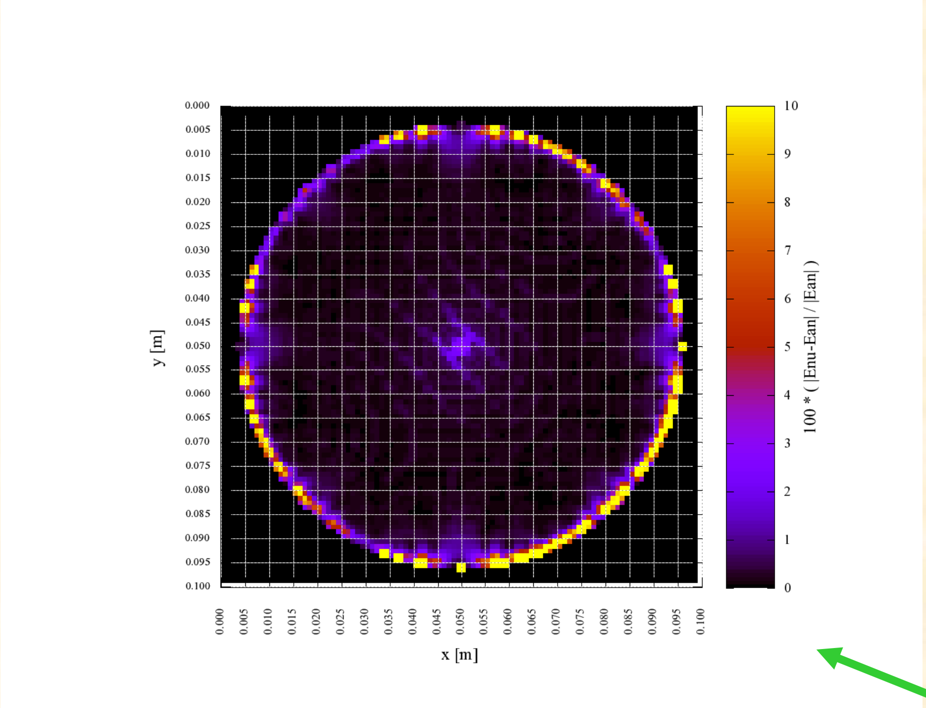
$\left|\vec{J}_B + \vec{J}_E\right|$

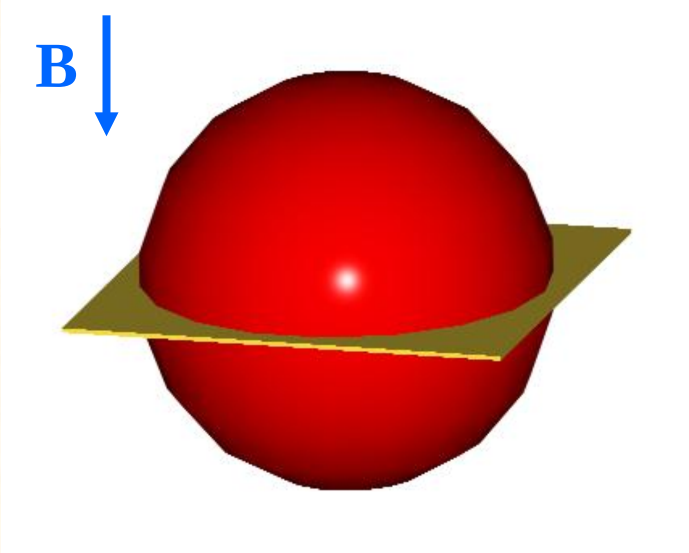
Composition of J_B & J_E

	|J| [mA/sqm]		
	(B+E)	*B*	*E*
Ankle (bone)	91,0		90,7
Foot (cartilage)	95,6		95,6
CerebroSpinalFluid	41,7	17,6	42,6
GallBladder	17		
GallBladderBile	19,7		13,3
Legs (Muscle)	144	18,9	144
Legs (Nerve)	18,5		18,6
Pancreas	14,9		11,7
SmallIntestine	16,3	15,8	16,1
Stomach	10,4	13,9	17,7

Validation

Validation: homogeneous sphere, B





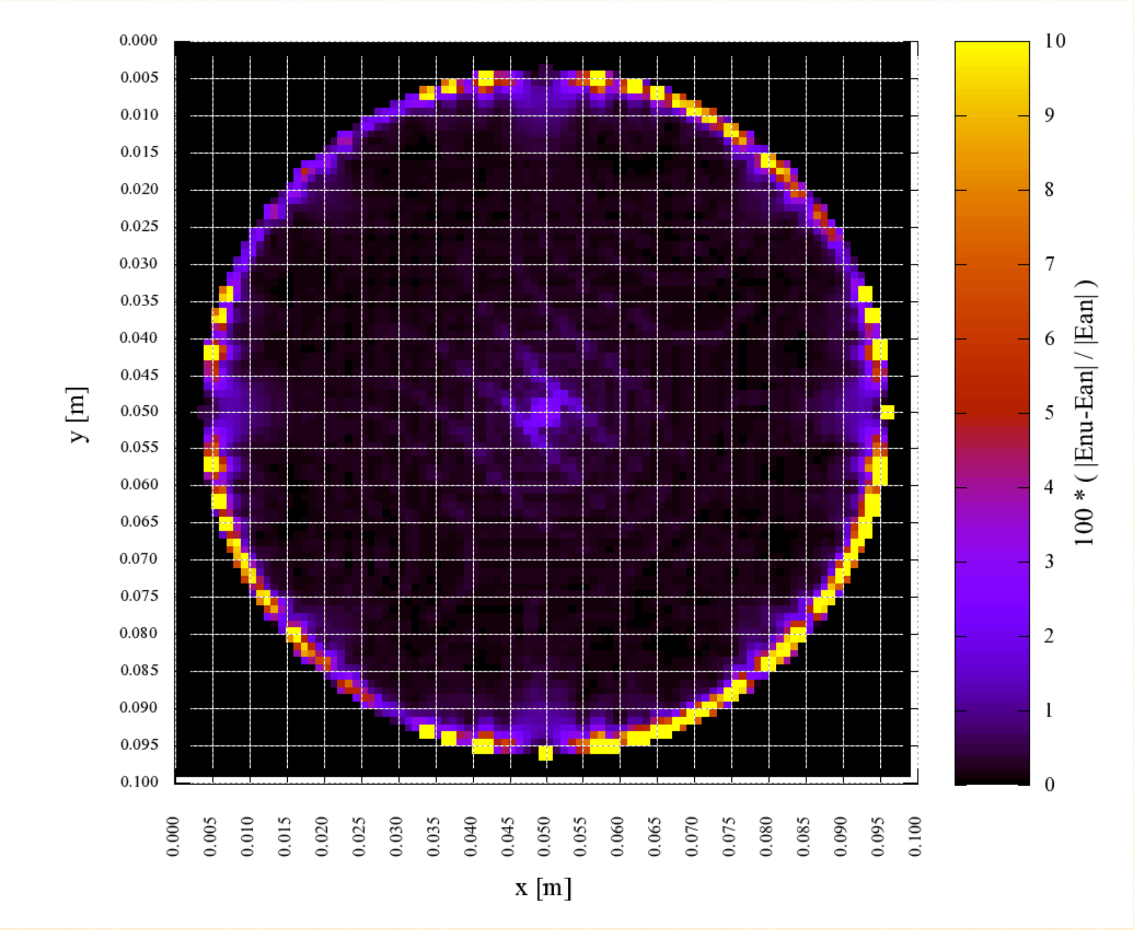
$$100 \cdot \frac{\left|\vec{E}_{analytical} - \vec{E}_{numerical}\right|}{\left|\vec{E}_{analytical}\right|}$$

The analytical solution was founded applying the Stevenson method:
A.F.Stevenson
"Solution of electromagnetic scattering problems as power series in the ratio (Dimension of scatter)/Wavelength"
Journal of Applied Physics – vol.24, n.9 Sept. 1953

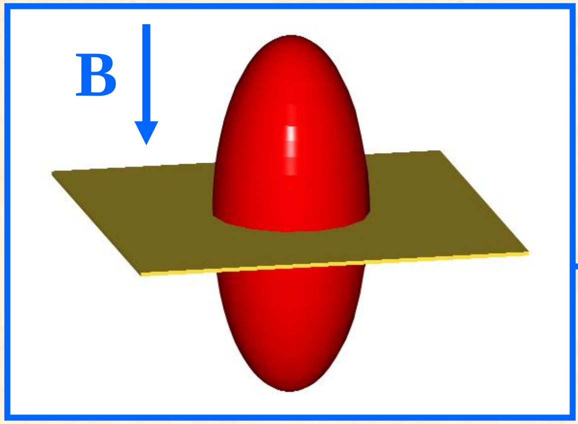
Validation: homogeneous sphere, B

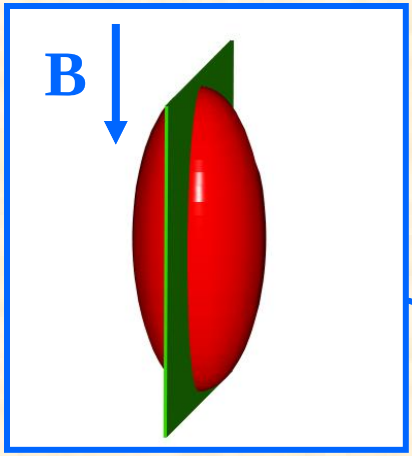
$$100 \cdot \frac{\left|\vec{E}_{analytical} - \vec{E}_{numerical}\right|}{\left|\vec{E}_{analytical}\right|}$$

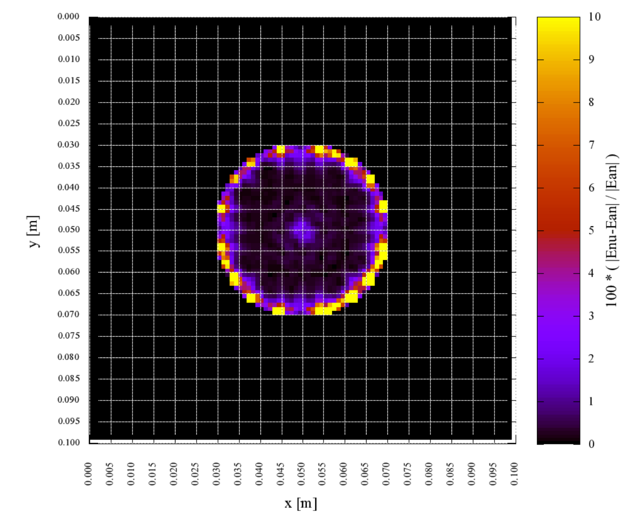
- Close to the center Eanalytical is close to 0.
- The agreement between analytical and numerical data get worse close to the sphere surface (effect of the discretization of the sphere).

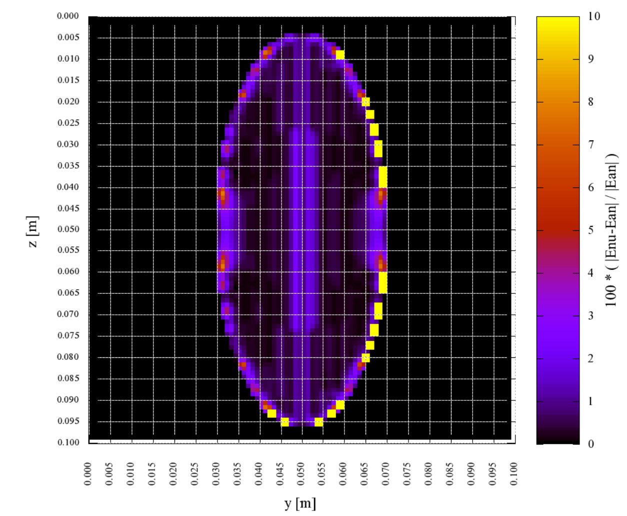


Validation: homogeneous prolate spheroid, B



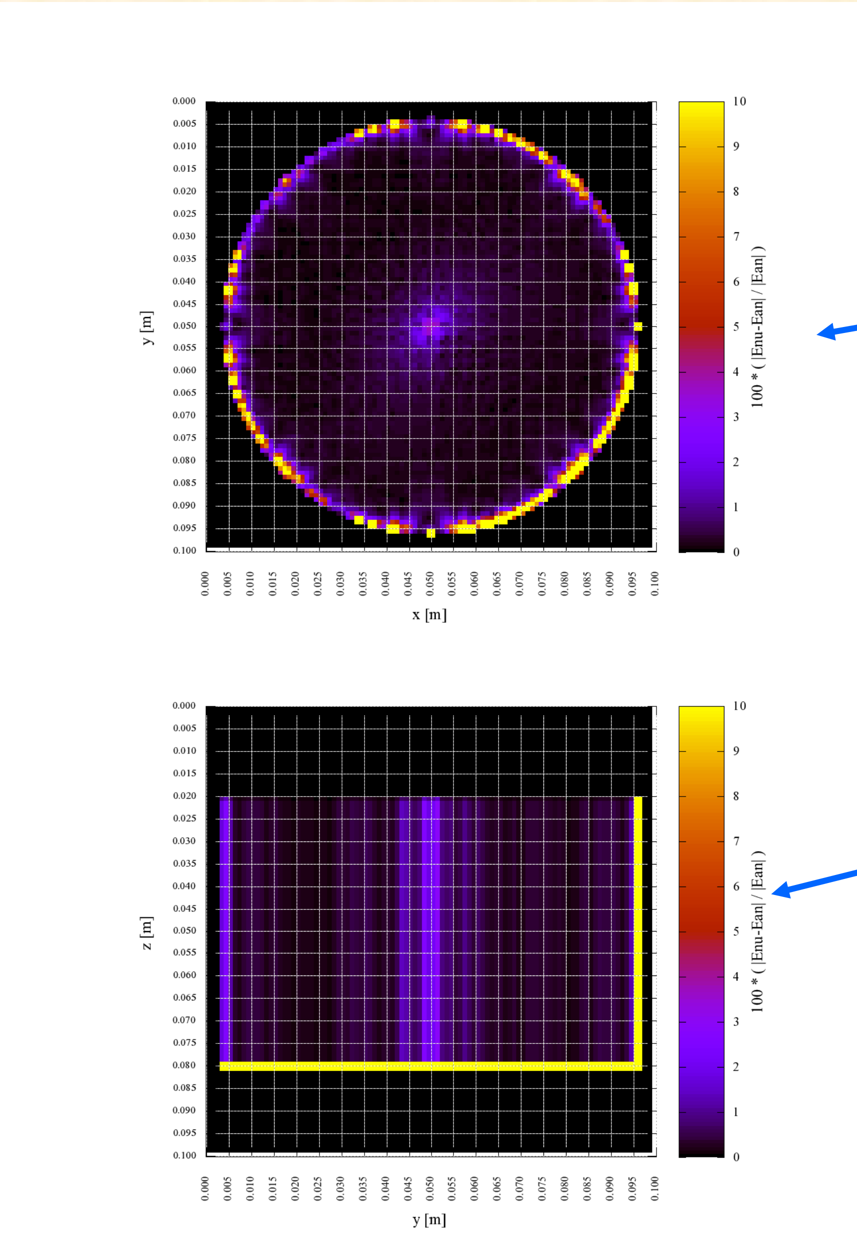


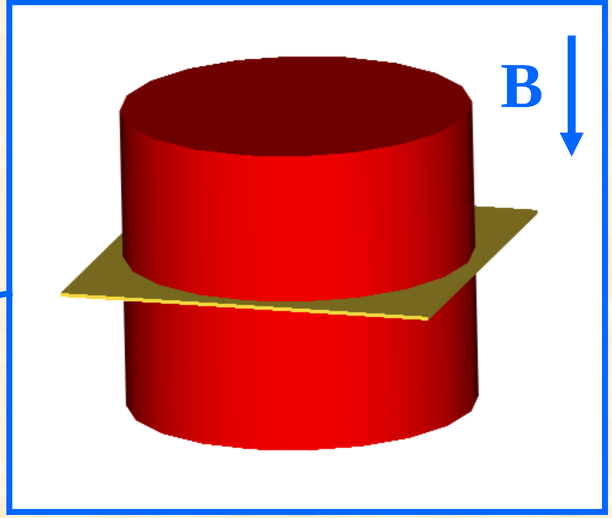


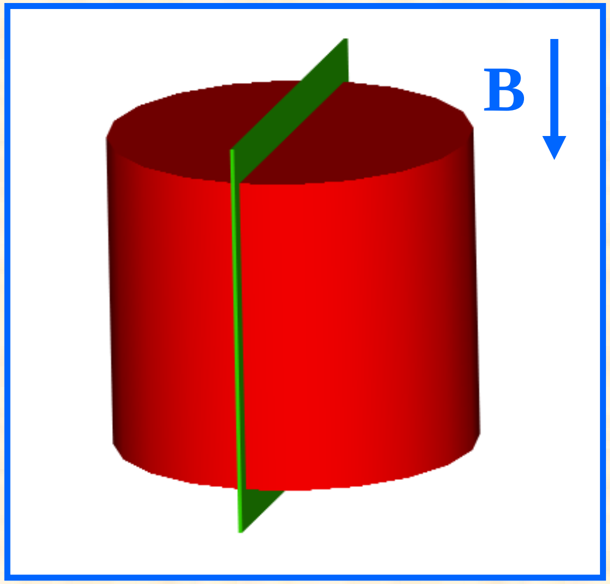


Reference for the analytical model:
C.H.Durney & al.
"*Long wavelength analysis of plane wave irradiation of a prolate spheroid model of man*"
IEEE Trans. On microwave theory and techniques
Vol. MTT-23 n.2 – feb. 1975 – pp. 246-253

Validation: homogeneous cylinder, B





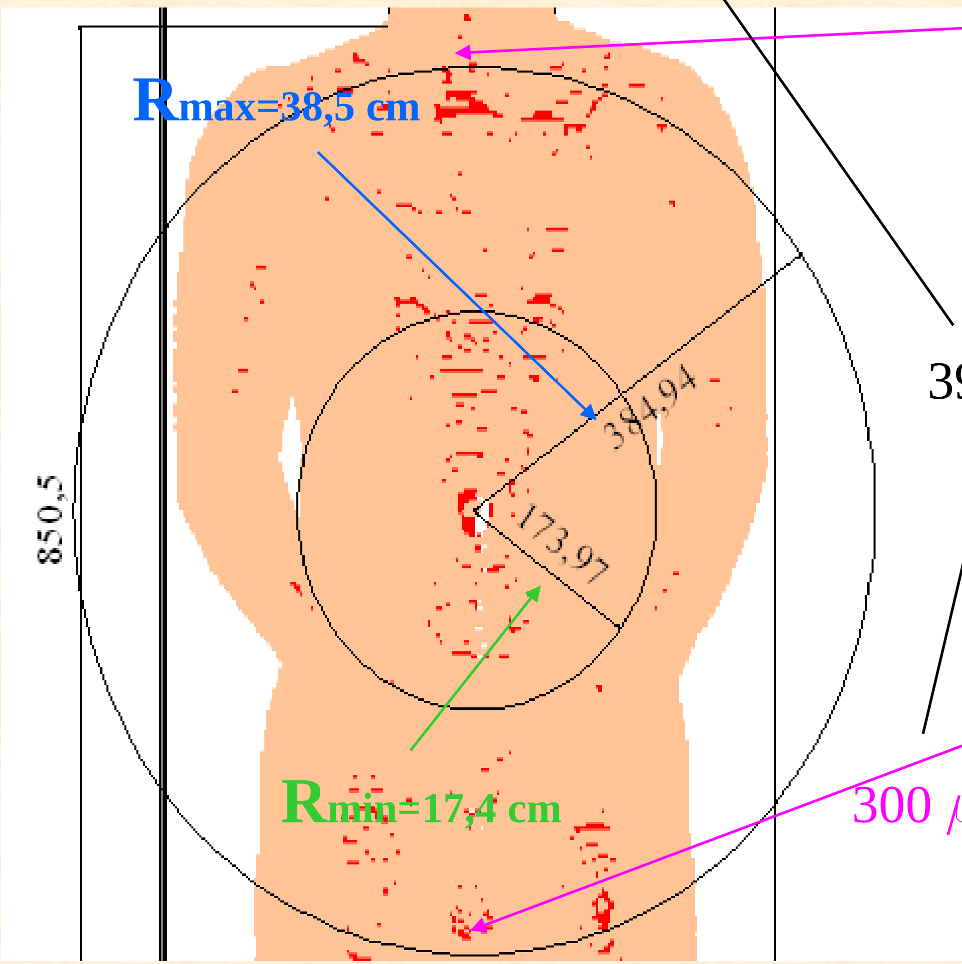


Gilbert

$$\boxed{J \approx \pi R f \sigma \vec{B} \cdot \hat{i}_n}$$

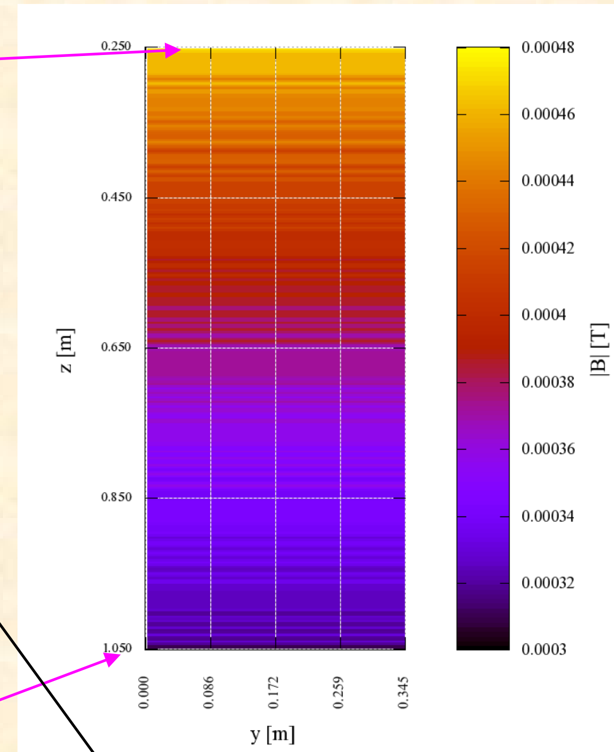
$\sigma_{\text{muscle@50 Hz}}=2{,}33\ 10^{-1}$

480 μT



390 μT

300 μT

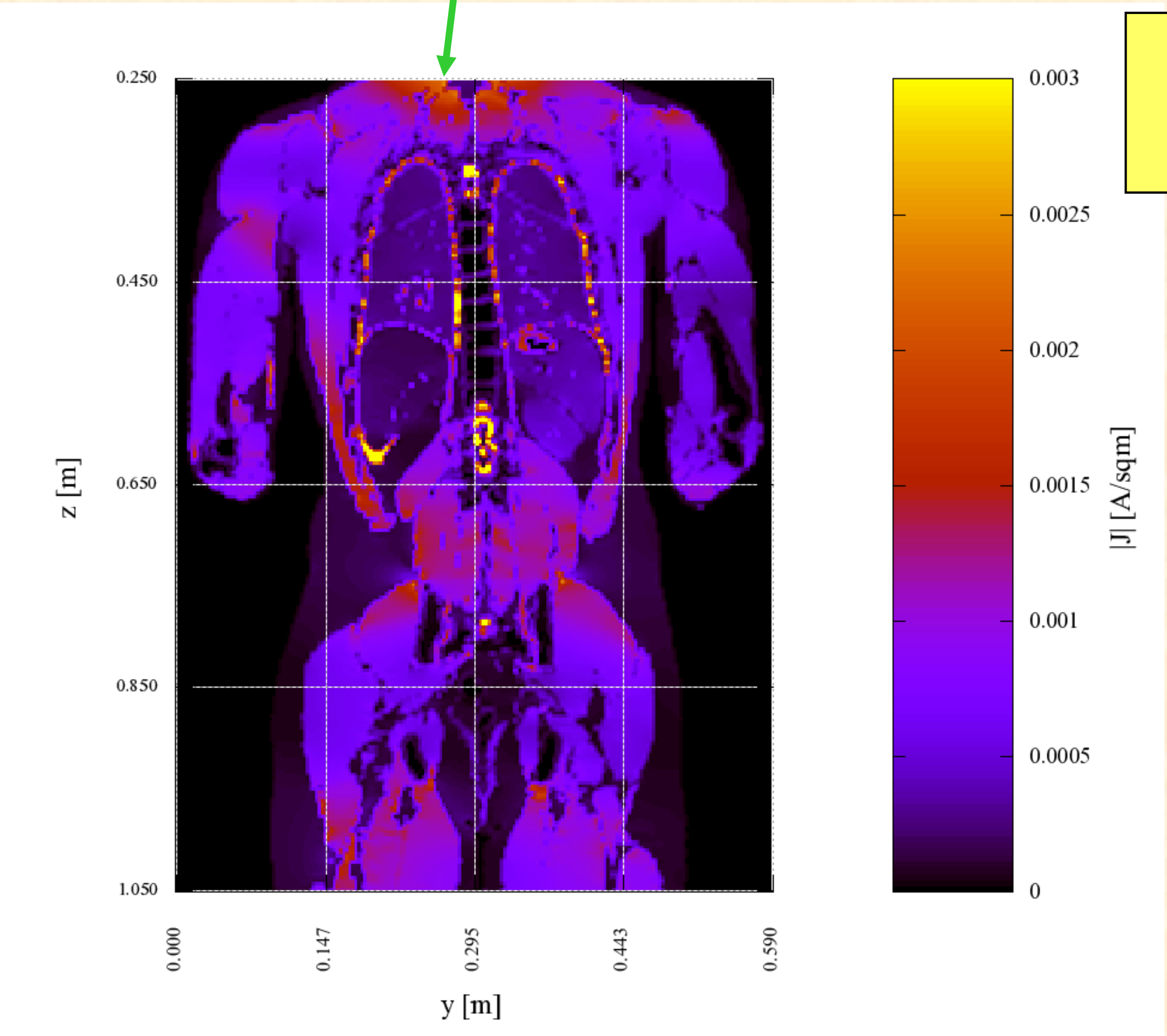


J_{max}=5,5 mA/sqm

J_{min}=2,5 mA/sqm

~2,5 mA/sqm

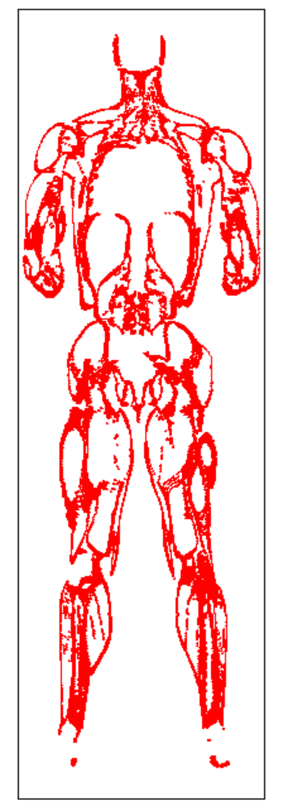
Gilbert



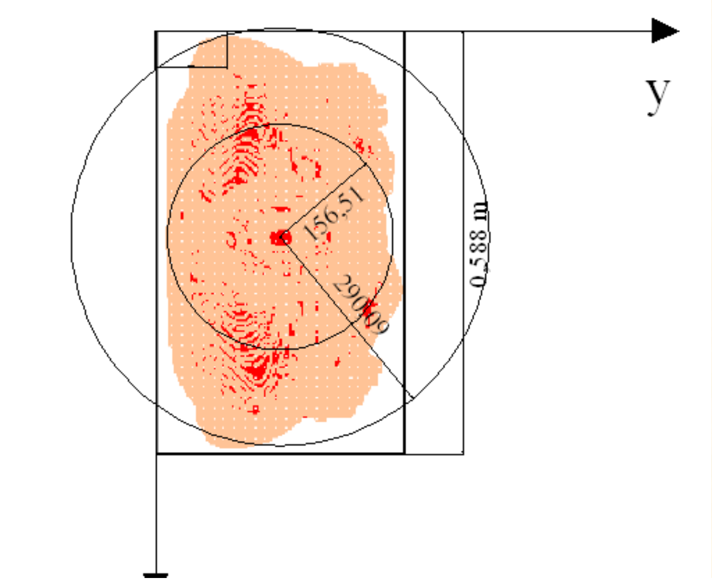
J_{max}=5,5 mA/sqm

J_{min}=2,5 mA/sqm

$\sigma_{muscle@50}$ Hz=2,33 10^{-1}



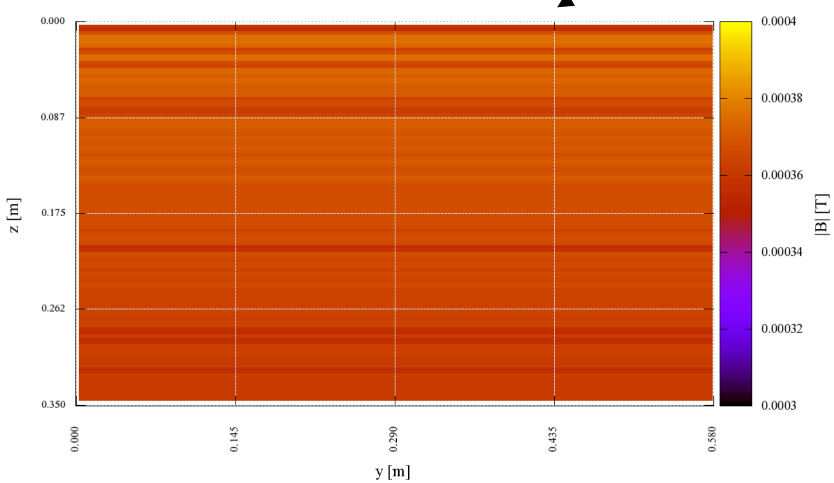
Gilbert



J_{max}=3,7 mA/sqm

J_{min}=1,9 mA/sqm

350 μT



~3 mA/sqm