

# **Uncertainties in assessment of worker exposure of low frequency electric and magnetic fields**

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# EU-directive

- **Directive 2004/40/EC of the European Parliament and of the Council of 29 April 2004 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (electromagnetic fields)**

# EU-directive

- **The employer shall assess and, if necessary, measure and/or calculate the levels of electromagnetic fields to which workers are exposed.**

# EU-directive

- **Assessment, measurement and calculation may, until harmonised European standards from CENELEC cover all relevant assessment, measurement and calculation situations, be carried out in accordance with the scientifically-based standards and guidelines.**

# EU-directive

- **On the basis of the assessment of the levels of electromagnetic fields ... if the action values are exceeded, the employer shall assess and, if necessary, calculate whether the exposure limit values are exceeded.**

# Uncertainty, standard procedure

- For an assessment value of  $X$ , a determined assessment uncertainty of  $U$  and a limit value of  $L$ , the uncertainty can be assessed against the limit as follows:

- To show that the actual value is below the limit value:

$$X + U \leq L$$

- To show that the actual value is above the limit value:

$$X - U > L$$

- If neither of the above conditions is fulfilled then the result of the comparison is uncertain.

# Uncertainty, shared risk

- For an assessment value of  $X$ , a determined assessment uncertainty of  $U$  and a limit value of  $L$ , the uncertainty can be assessed against the limit as follows:

- To show that the actual value is below the limit value:

$$X \leq L$$

- To show that the actual value is above the limit value:

$$X > L$$

- In this case there must be demands on the maximum allowed uncertainty  $U < U_{\text{demand}}$

# Uncertainties in measurements of electric fields.



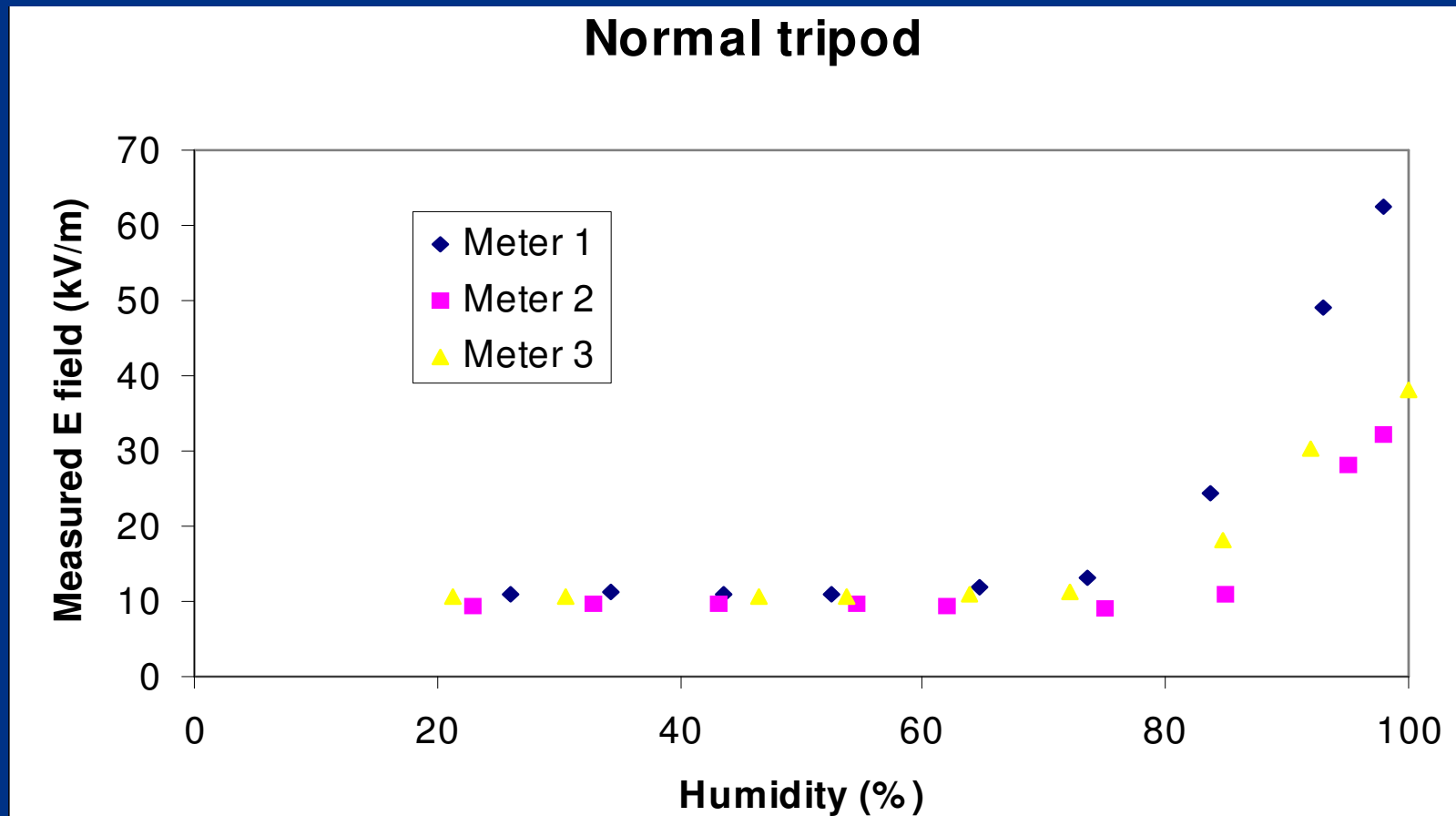
# Measurements of electric fields 5 Hz – 400 kHz.



# Influence of humidity



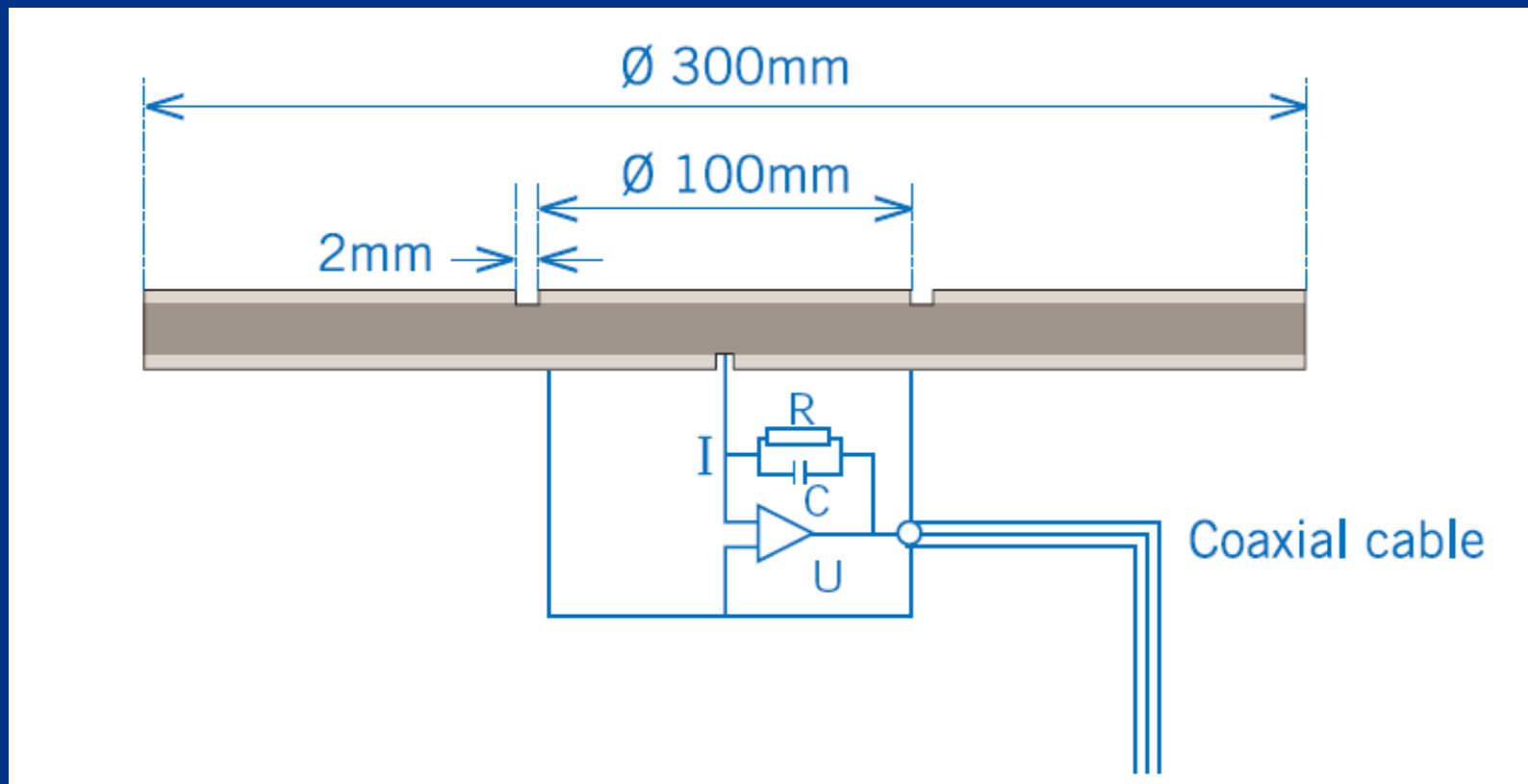
## Normal tripod



Electric field strength increased 25  
% due to disturbance of field



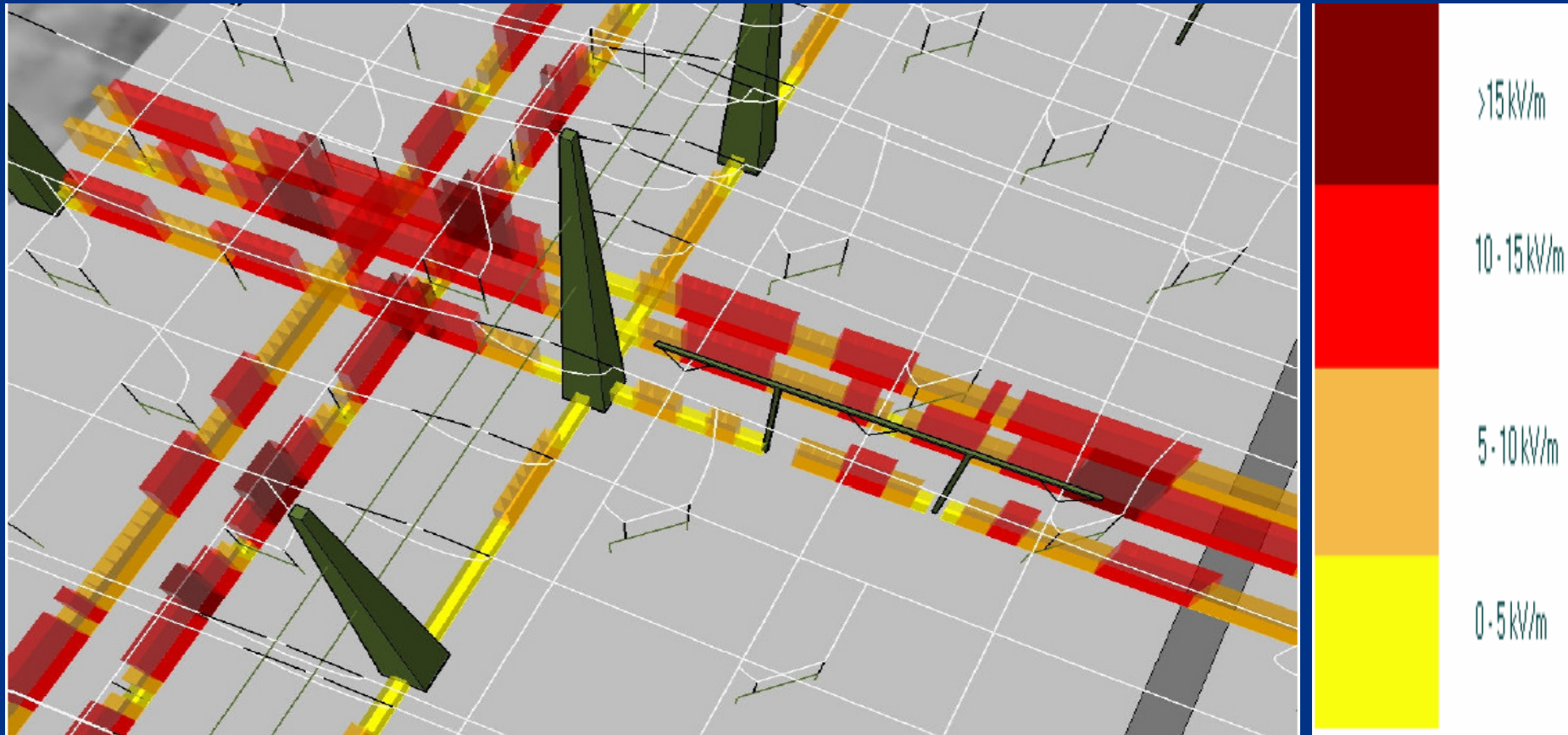
**Measurement of E-field  $i = \epsilon(dE/dt)A$   
depends on if the instrument is connected to  
ground potential or not.**



## Spatially averaging of the field

- **ICNIRP states, “the reference levels are intended to be spatially averaged values over the entire body of the exposed individual, but with the important proviso that the basic restrictions on localized exposure are not exceeded.”**
- **Almost impossible to measure for E-field.**

# Electric fields in switchyards



# Do we need to reduce the E-field to 10 kV/m

- **Nothing is mentioned in the directive, but ICNIRP gives a possibility**
- **“For the specific case of occupational exposures at frequencies up to 100 kHz, the derived electric fields can be increased by a factor of 2 under conditions in which adverse indirect effects from contact with electrically charged conductors can be excluded.”**

# Action values

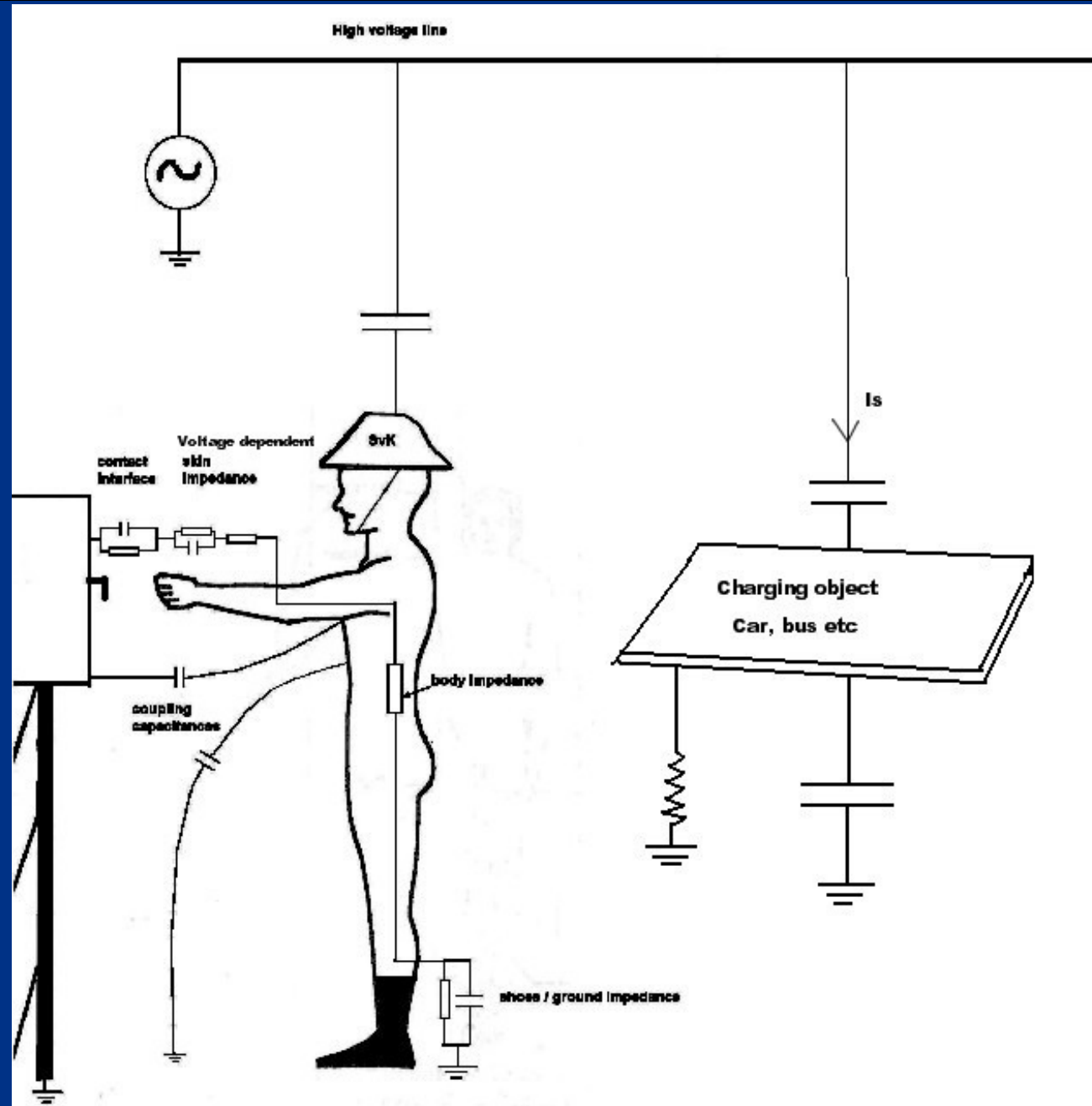
Frequency range	Electric field strength, E (V/m)	Magnetic field strength, H (A/m)	Magnetic flux density, B ( $\mu\text{T}$ )	Equivalent plane wave power density, $S_{\text{eq}}$ ( $\text{W}/\text{m}^2$ )	Contact current, $I_{\text{C}}$ (mA)	Limb induced current, $I_{\text{L}}$ (mA)
0 – 1Hz	–	$1,63 \times 10^5$	$2 \times 10^5$	–	1,0	–
1 – 8 Hz	20000	$1,63 \times 10^5 / f^2$	$2 \times 10^5 / f^2$	–	1,0	–
8 – 25 Hz	20000	$2 \times 10^4 / f$	$2,5 \times 10^4 / f$	–	1,0	–
0,025 – 0,82kHz	$500 / f$	$20 / f$	$25 / f$	–	1,0	–
0,82 – 2,5 kHz	610	24,4	30,7	–	1,0	–
2,5 – 65 kHz	610	24,4	30,7	–	$0,4 f$	–
65 – 100 kHz	610	$1600 / f$	$2000 / f$	–	$0,4 f$	–
0,1 – 1 MHz	610	$1,6 / f$	$2 / f$	–	40	–
1 – 10 MHz	$610 / f$	$1,6 / f$	$2 / f$	–	40	–
10 – 110 MHz	61	0,16	0,2	10	40	100
110 – 400 MHz	61	0,16	0,2	10	–	–
400 – 2000 MHz	$3f^{1/2}$	$0,008f^{1/2}$	$0,01f^{1/2}$	$f/40$	–	–
2 – 300 GHz	137	0,36	0,45	50	–	–

# Measurements of contact currents in substations

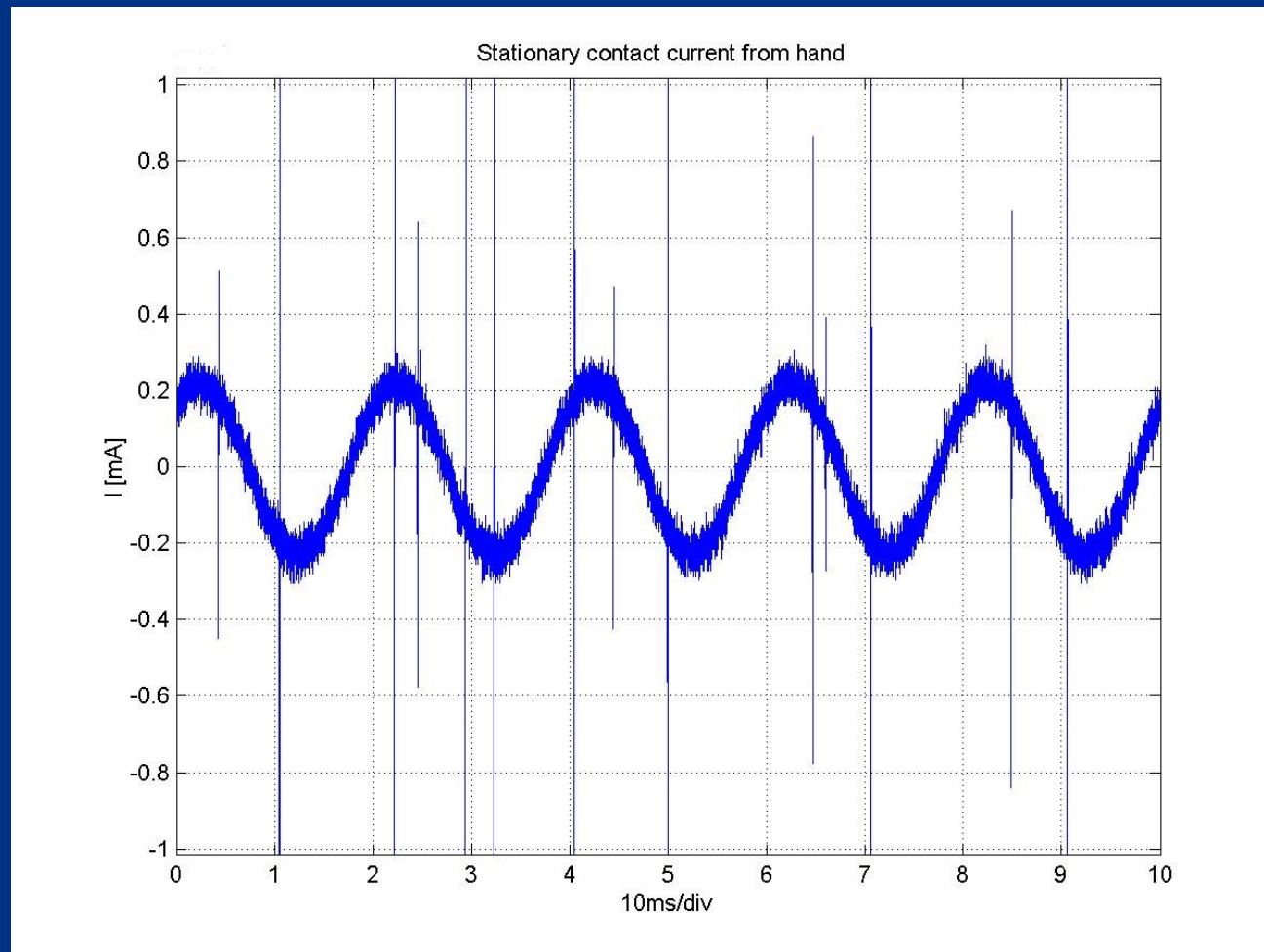


# Contact currents in substations

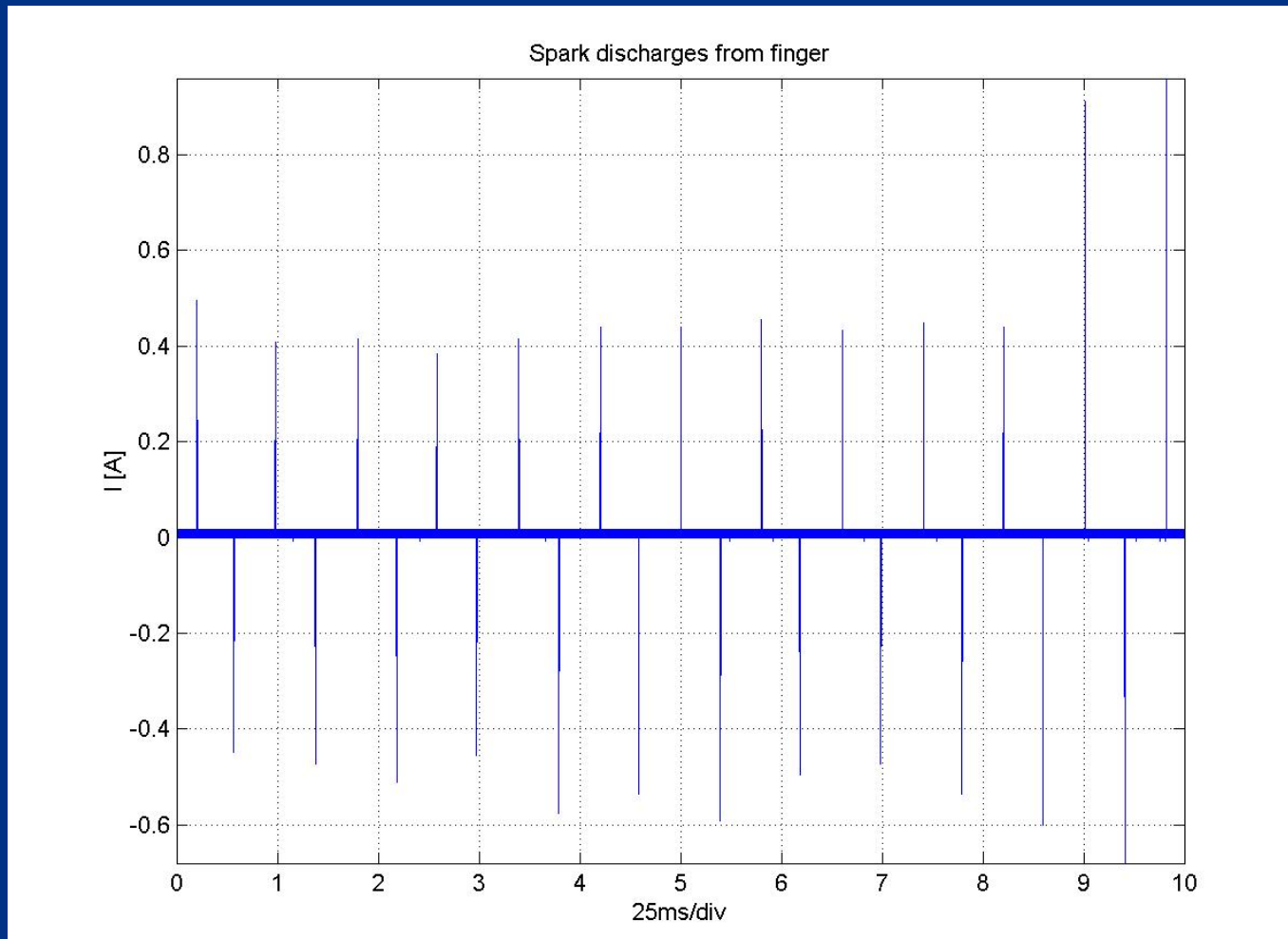




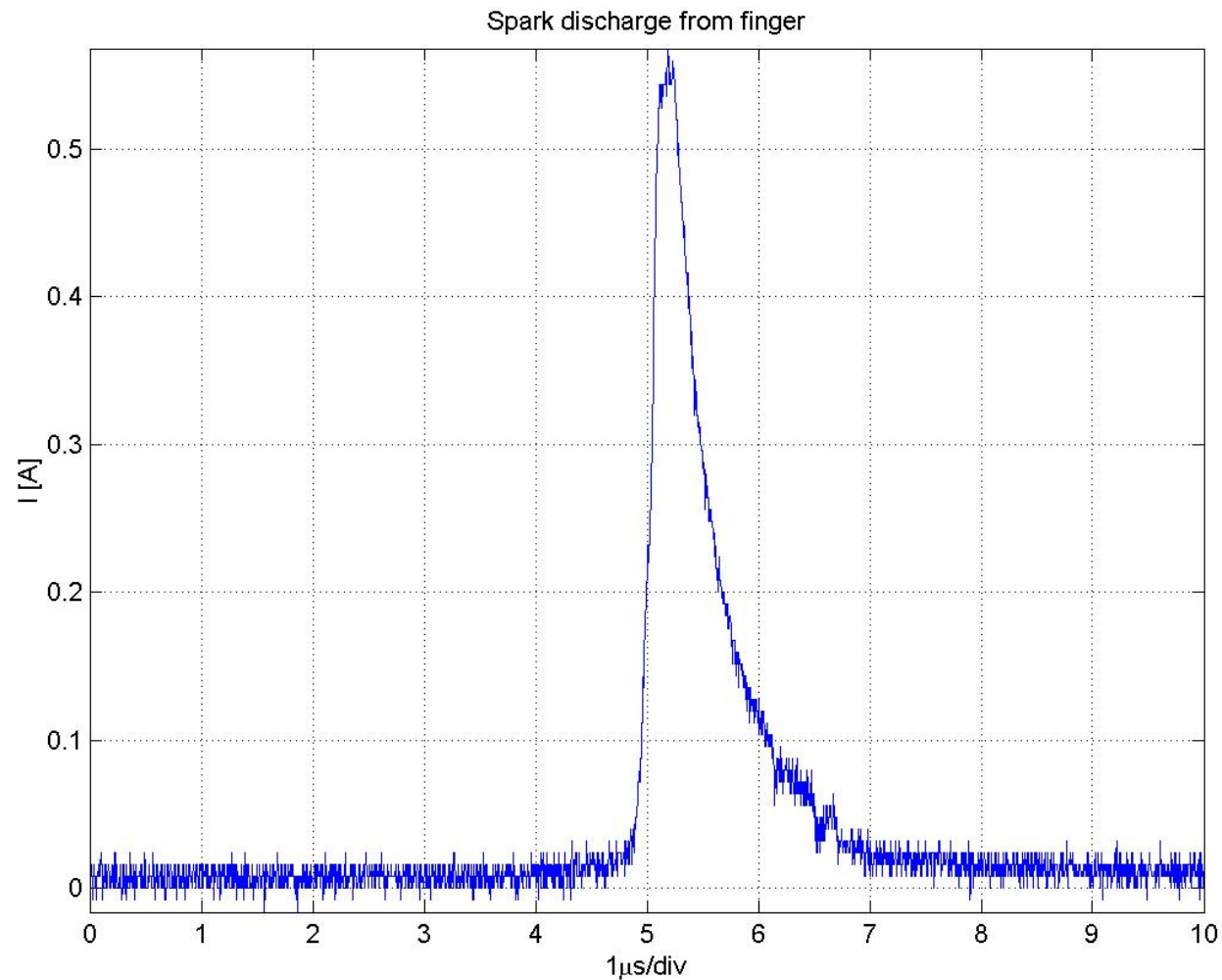
# Stationary contact current against hand



# Spark discharges against a finger



# Spark discharges against a finger

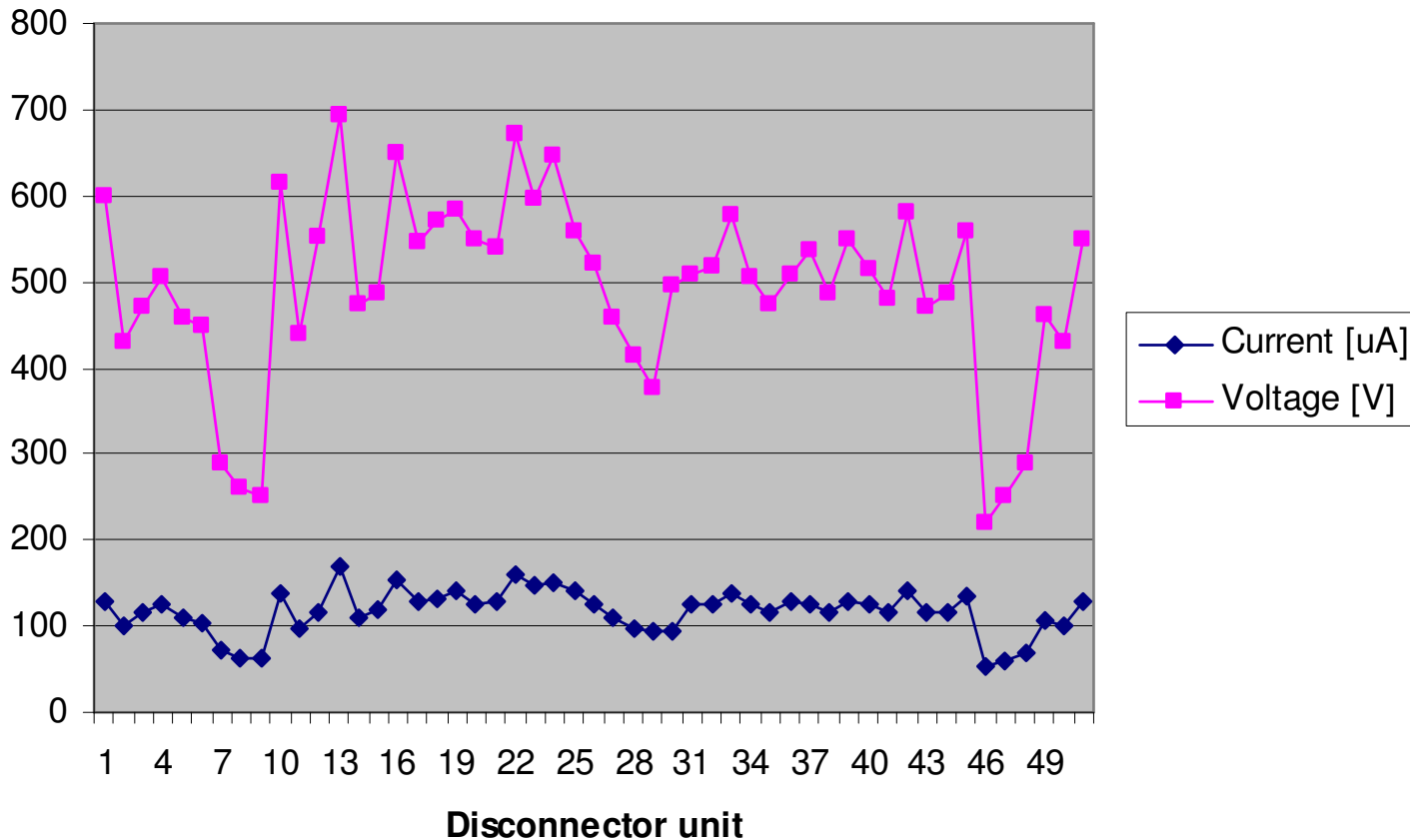


Spark discharges are not only painful,  
they could give rise to accidents



# Stationary current ( $\mu\text{A}$ ) and open circuit voltage (V)

Short circuit current and open circuit voltage (rms)



# Uncertainties E-field measurements

Large uncertainties because the instrument and the operator will disturb the E-field.

Instruments are directional.

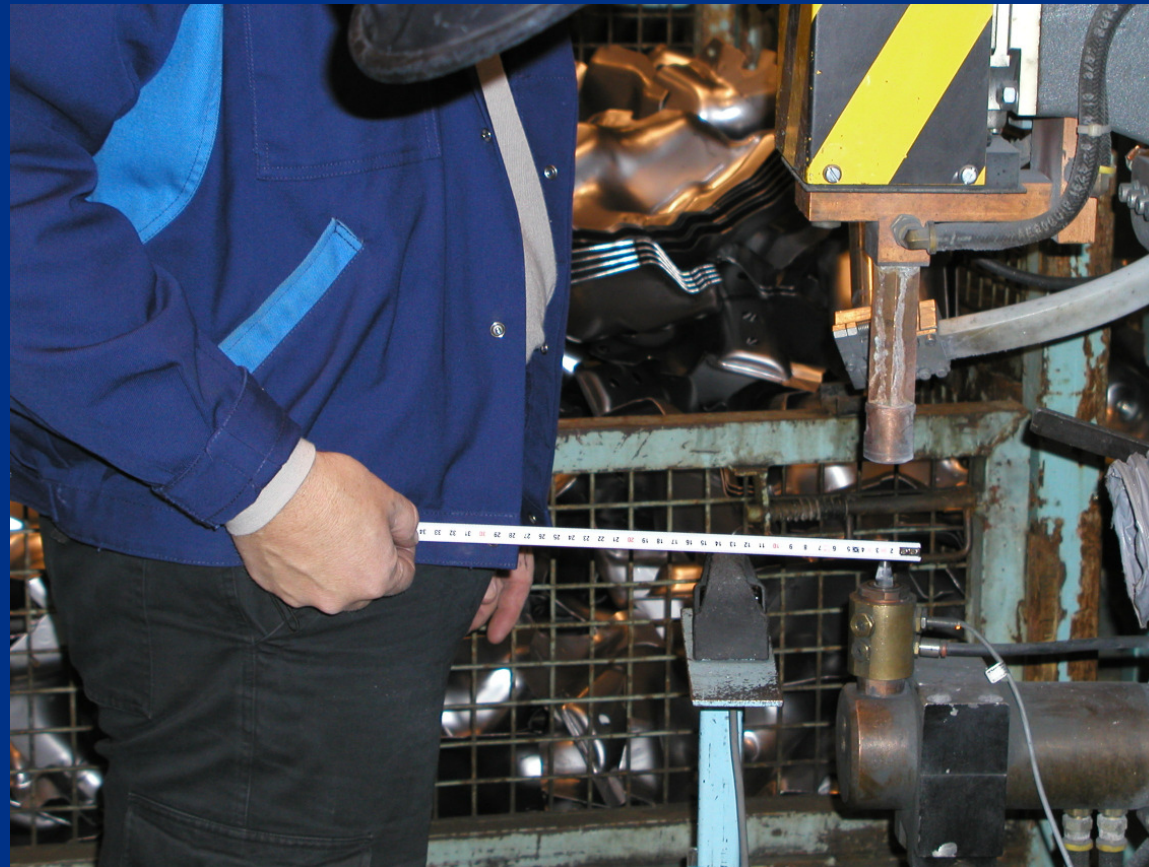
Grounded or non-grounded instrument?

Calibration or stated accuracy of the measurement instrument.

Measurement of the average field over the body almost impossible.

Measurements of contact currents, how shall the spark discharges be treated?

# Measurements of magnetic fields



# Suggested measurement point for arc welding prEN 50444

prEN 50444:2006

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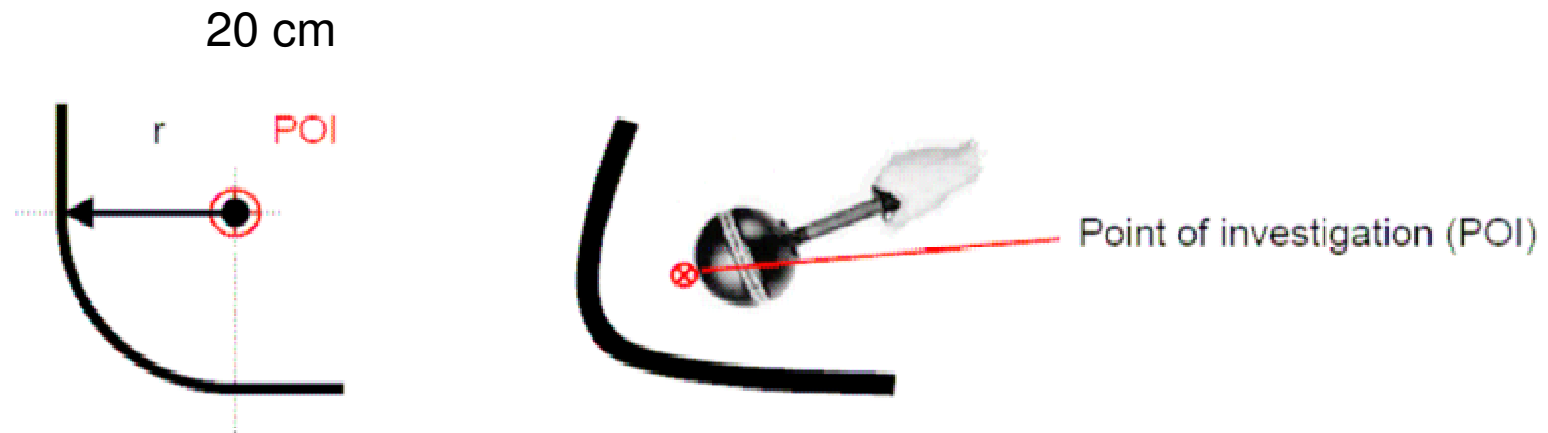


Figure A.1 – Probe position for worst case measurement on cables



## ICNIRP:

For electrical stimulation, relevant for frequencies up to 10 MHz, induced current densities should be added according to

$$\sum_{i=1 \text{ Hz}}^{10 \text{ MHz}} \frac{J_i}{J_{L,i}} \leq 1.$$

$J_i$  = the current density induced at frequency  $i$ ;  
 $J_{L,i}$  = the induced current density restriction at frequency  $i$  as given in Table 4;

# Summation of frequency components including phase

$$J_t = \sum_{i=1\text{Hz}}^{10\text{MHz}} \frac{J_i}{J_{L,i}}$$

- Summation without phase.

$$\left| \sum_i \frac{J_i}{J_{L,i}} \cos(2\pi f_i t + \theta_i + \varphi_i) \right| \leq 1$$

- Summation with phase.

$\theta_i$  is the phase angle of the spectral component at frequency  $f_i$

$\varphi_i$  is the phase angle of the weighting function at frequency  $f_i$  as defined in the reference document for the limit values, see Annex F

## ICNIRP Statement

GUIDANCE ON DETERMINING COMPLIANCE OF EXPOSURE  
TO PULSED AND COMPLEX NON-SINUSOIDAL WAVEFORMS  
BELOW 100 KHZ WITH ICNIRP GUIDELINES

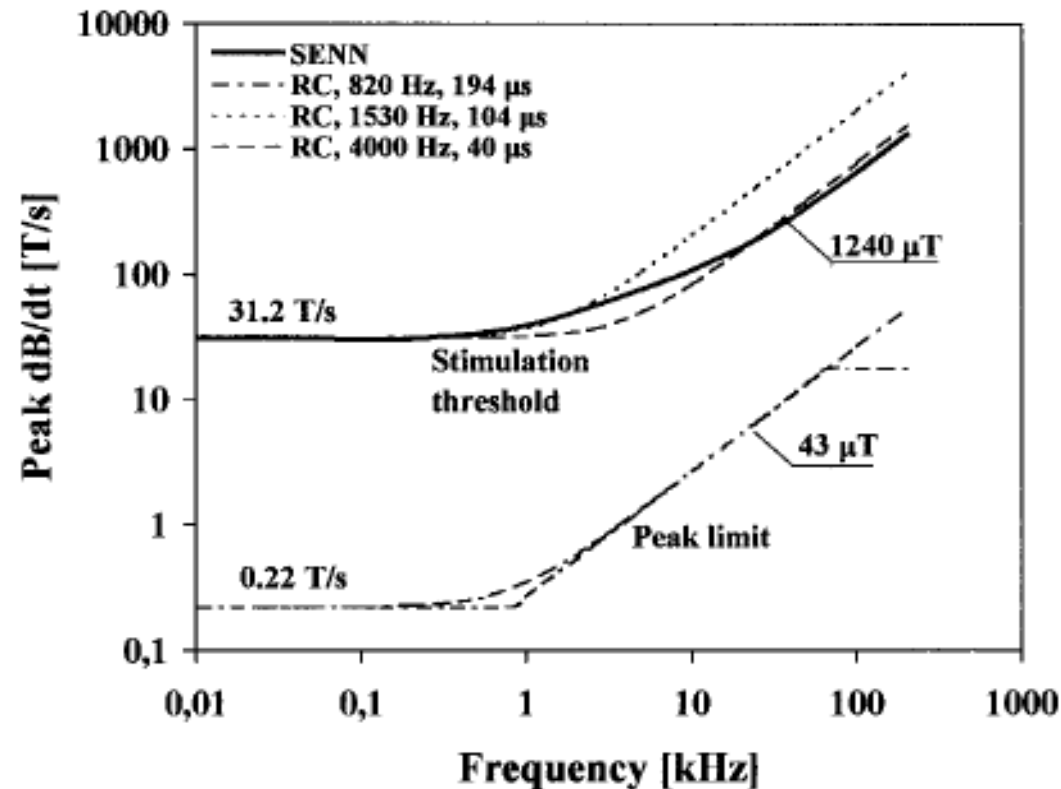
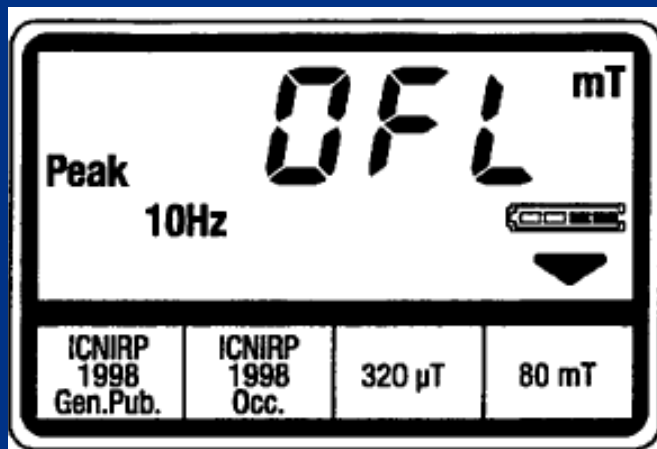


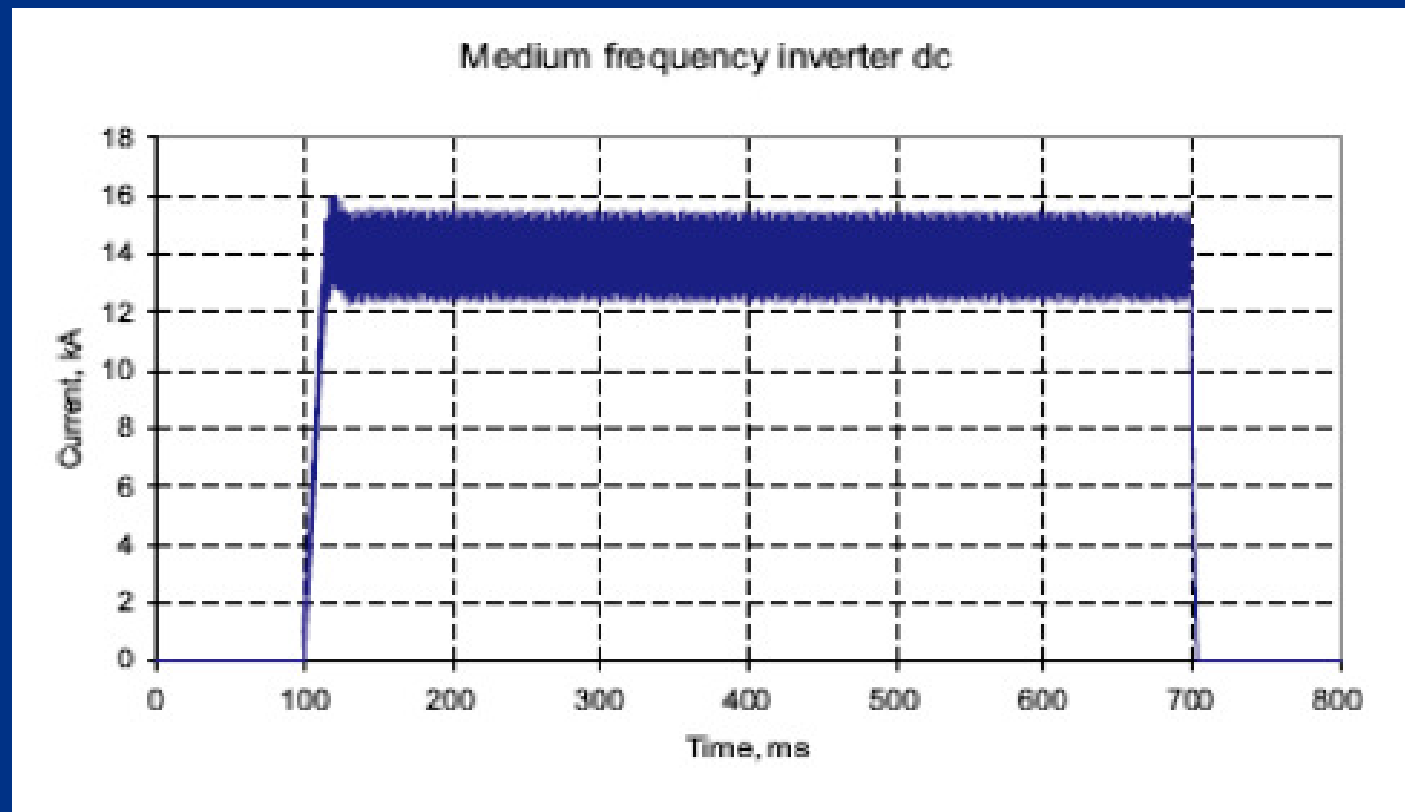
Fig. 3. Stimulation threshold and peak limit for a sinusoidal magnetic field as a function of frequency (Jokela 2000). The solid curve shows the stimulation threshold calculated with the SENN (spatially extended nonlinear nodal) model of Reilly (1998). The lower curve is the peak limit for occupational exposures.

# Instrument for 1 Hz – 400 kHz

**Built in correction  
for ICNIRP  
reference levels**



# How to treat the rise and fall Demands on instruments? Pulse from a MFDC welding equipment



## EU-directive

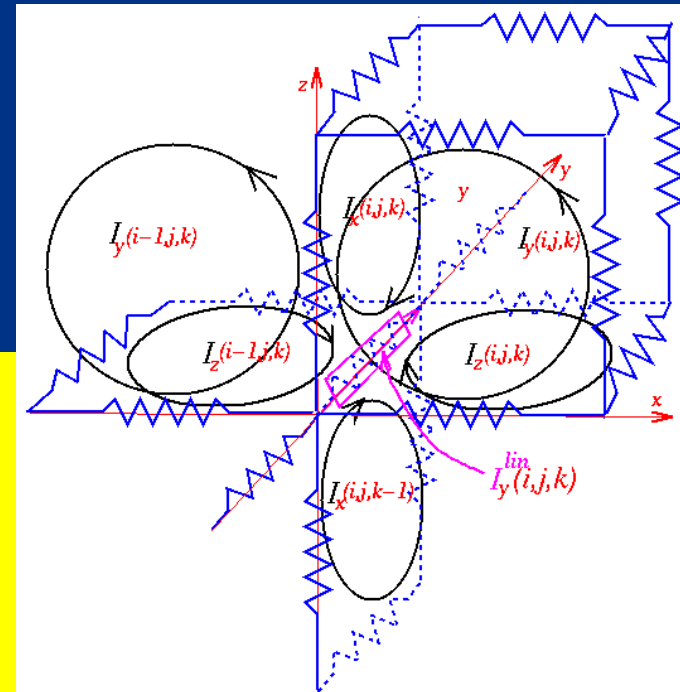
- The exposure limit values on the current density are intended to protect against acute exposure effects on central nervous system tissues in the head and trunk of the body.
- Such acute effects are essentially instantaneous and there is no scientific justification to modify the exposure limit values for exposure of short duration.
- Since the exposure limit values refer to adverse effects on the central nervous system, these exposure limit values may permit higher current densities in body tissues other than the central nervous system.

# Uncertainties in measurements of magnetic fields

- The instrument and the person performing the measurements have a negligible influence on the field distribution.
- Many magnetic field instruments are more or less isotropic which also simplifies the measurements.
- One source to uncertainty is the size and shape of the measurement elements and the actual position of the probe.
- Calibration or stated accuracy of the measurement instrument.
- Spatial averaging.
- Complex, (non-repeatable) waveforms.

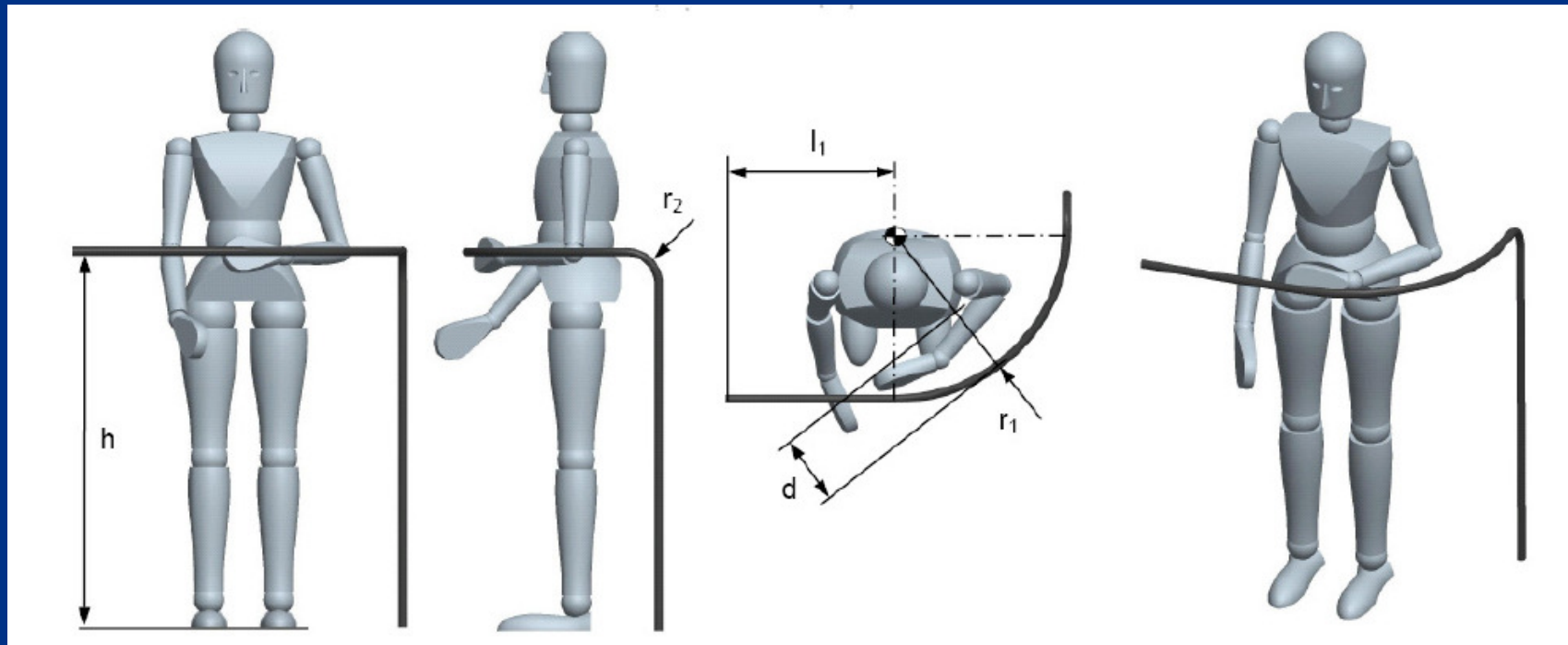
# Uncertainties in simulations

$$\begin{aligned}
 & [I_x(i, j, k-1) - I_x(i, j, k) + \\
 & \quad -I_z(i-1, j, k) + I_z(i, j, k)] Z_y(i, j, k) \\
 & + [I_x(i, j+1, k) - I_x(i, j, k) + I_y(i-1, j+1, k) \\
 & \quad - I_y(i, j+1, k)] Z_z(i, j+1, k) \\
 & + [I_x(i, j, k+1) - I_x(i, j, k) + I_z(i-1, j, k+1) - I_z(i, j, k+1)] Z_y(i, j, k+1) \\
 & + [I_x(i, j-1, k) - I_x(i, j, k) - I_y(i-1, j, k) + I_y(i, j, k)] Z_z(i, j, k) = -i\omega \Delta y \Delta z \mathbf{B} \cdot \hat{\mathbf{x}}
 \end{aligned}$$



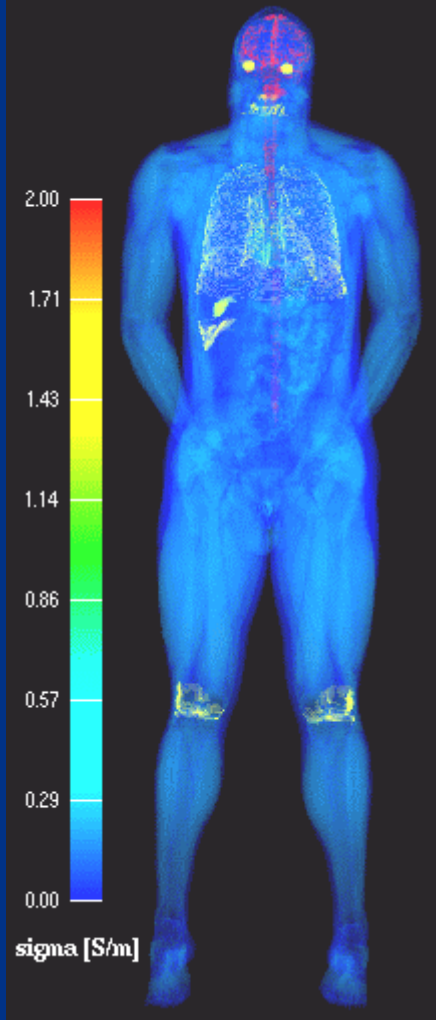
# Modeling and positioning the source

Suggested source for arc welding prEN 50444

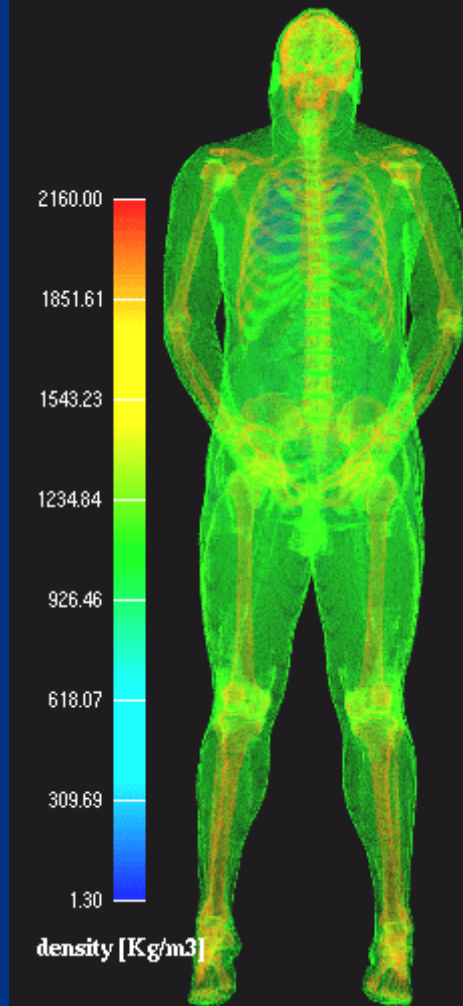


# Just a few models exists, mostly standing adult male

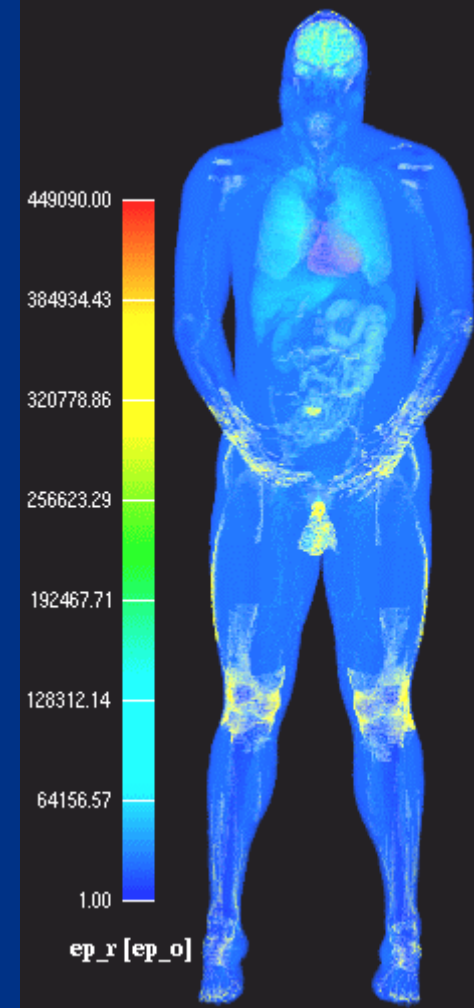
Conductivity in 3mm man model



Mass density in 3mm man model



Permittivity in 3mm man model



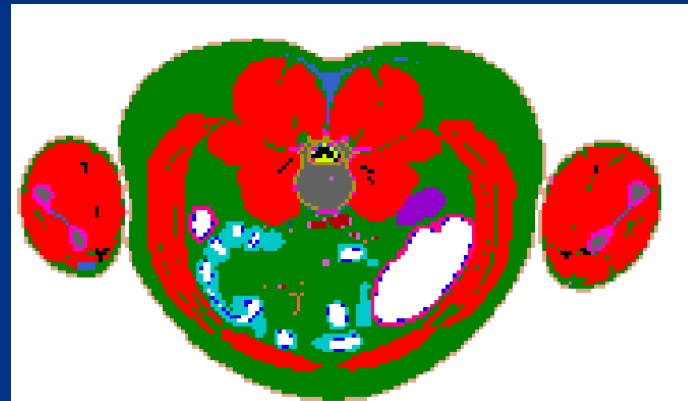
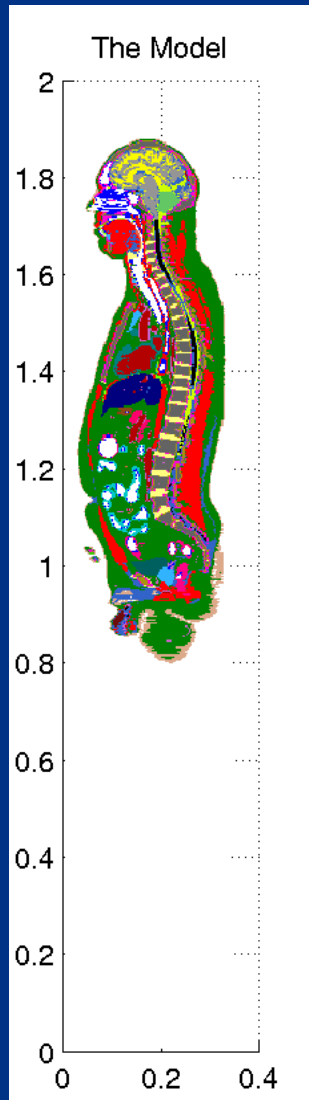
# Uncertainties in the model

- Lack of female and children models.
- Lack of different postures.
- Uncertainties in modeling of source.
- Voxel size too coarse to model all anatomical details.
- Staircase errors.
- Errors in the models due to discontinuity from one layer to next in organ coding.

# Variations in maximum induced current density in CNS, for a welder, scaling the size of visual man (original height 1.8m)

Height (m)	Deviation
1.5	-10 %
1.6	-6 %
1.7	-3 %
1.8	0 %
1.9	+3 %
2.0	+5 %

# Uncertainties in tissue parameters



	air.(external)		cerebellum		heart		muscous.membrane
	air.(internal)		cerebral.spinal.fluid		intestine.large		nails.(toe.&.finger)
	bile		eye.aqueous.humor		intestine.small		nerve
	bladder		eye.comea		kidneys		pancreas
	blood		eye.lens		ligaments		perfect.conductor
	blood.vessel		eye.retina		liver		skin.dermis
	body.fluid		eye.sclera-wall		lung.inner		spleen
	bone.cancellous		fat		lung.outter		stomach
	bone.cortical		gall.bladder		lymp		testicles
	bone.marrow		glands		muscle		tooth
	cartilage		gray.matter		muscle.2-3		white.matter

# Uncertainties in tissue parameters

- Tissue parameters are frequency dependent.
- Can be anisotropic.
- A modulation of the tissue parameters by 10% gave a variation in the induced averaged current density in CNS of 13%.

# Uncertainties due to neglecting the permittivity of tissues.

- The tissue complex impedance can be described as:

$$\frac{R}{1 + j\omega RC}$$

- Where  $RC = \varepsilon/\sigma$
- If the the imaginary term  $j\omega RC$  has been neglected in order to get a real non-complex impedance a substantial uncertainty is introduced.

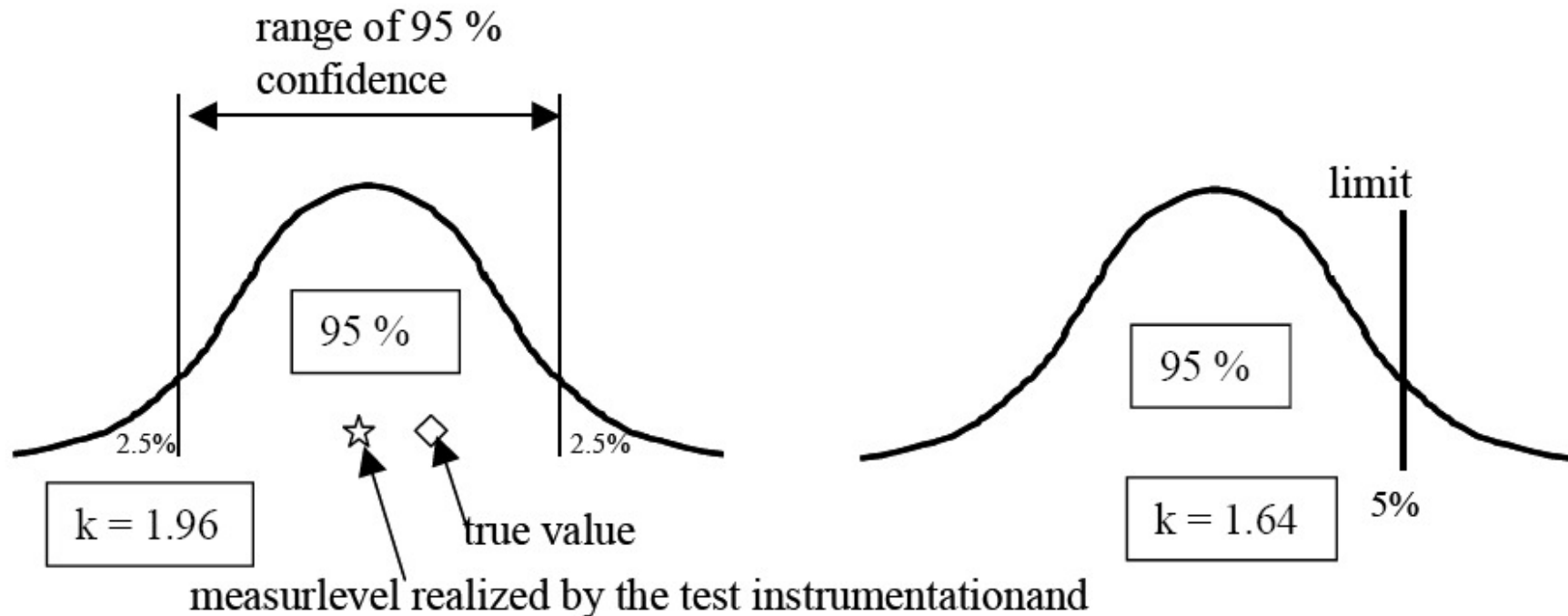
## Uncertainties due to averaging over 1 cm<sup>2</sup>.

- Uncertainty due to defining a surface perpendicular to the current density vector around which the average is performed.
- Restricting to CNS tissue.
- The voxel size will limit the precision.

# Calculation of the combined uncertainty $u_c(y)$ and the expanded uncertainty, $U_c = u_c(y) k$ . (from CISPR/A/704/CD)

coverage factor k for 95% confidence

coverage factor k for 95% confidence to a limit



## Reasonable expanded uncertainty according to draft prEN 50444:2006

**Table 3 – Reasonable expanded assessment uncertainties**

Frequency range	Measurement	Modelling
< 10 kHz	+58 %, -37 % ( $\pm 4$ dB)	$\pm 50$ %
10 kHz - 1 MHz	+41 %, -30 % ( $\pm 3$ dB)	$\pm 50$ %
1 MHz - 30 MHz	+41 %, -30 % ( $\pm 3$ dB)	$\pm 40$ %
30 MHz - 1 GHz	+100 %, -50 % ( $\pm 6$ dB)	$\pm 40$ %
1 GHz - 30 GHz	+100 %, -50 % ( $\pm 6$ dB)	$\pm 50$ %

# Conclusions

- Measurements of E-field is complex, substantial uncertainties
- Measurements of B-field is easier, however complex wave forms can give high uncertainty
- The total uncertainty for simulations is also substantial.
- As the uncertainty is substantial standard or shared risk approach gives quite different limits.