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B-Field Exposure From Induction Cooking Appliances

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1 Executive Summary

Induction cooking uses the fact that alternating magnetic fields generate heat in the ferromagnetic cooking vessel due to magnetic hysteresis and induced eddy currents. Safety concerns about exposure to magnetic stray-fields have arisen. Studies by Suzuki [1] and Yamazaki [3] have assessed these magnetic fields with contradicting findings.

The objective of this study was to assess the maximum exposure that arises during use of induction cooking devices. Three devices currently available on the Swiss market were selected: the built-in appliances 1 and 2 (Electrolux GK58TCi and Gaggenau CI 261 110) and the portable appliance 3 (Inducs SH/BA 5000). The appliances were mounted on wooden supports allowing measurement in close proximity to the hobs without disturbing the B-field.

Fifteen pots and pans of different sizes and shapes, as well as of various materials were evaluated in single and multi-hob use in order to select a worst-case set of pots corresponding to the worst-case B-field exposure. A standard set of pots was also defined according to the European Norm EN50366. The Narda probe ELT-400 specifications were validated, and the probe was used for the characterization of the induction cookers in the time- and frequency-domains (cooking signal frequency, dependency on the heat setting, etc.).

In the first step, the spatial B-field exposure was evaluated according to EN50366 [4] (i.e., at a measuring distance of 30 cm using the standard set of pots). All three appliances met the compliance criteria of ICNIRP [2] for incident B-fields by a margin larger than 14 dB (see Table 11).

In the second step, the worst-case exposure was evaluated as a function of pot and heating configurations. It was demonstrated that different pot and and heating configurations can result in exposures that well exceed +10 dB of the standard EN50366 configurations at the same distance (see Figure 55). In addition, the field distribution has a strong negative gradient in the direction of larger distances. Therefore, DASY4 was enhanced to enable 3D field scanning using the NARDA probe. At the very short distance of 1 cm, the fields can be more than 30 dB larger than at 30 cm (see Table 14). Combining the results from worst-case configurations and short distance measurements, the standard EN50366 values can be exceeded by 37 dB (see Figure 55). The uncertainty of the evaluation was determined to be 1.5dB (k=2).

The third task was to evaluate the findings with respect to compliance testing. Assuming the distribution of Appliance 3, exposure close to the appliance could be as much as 37 dB or a factor of 70 above the ICNIRP safety limits. A very simple approximation suggest that the induced currents for such a worst-case compliant appliance would exceed the basic restrictions by nearly a factor of 10. In other words, the current standard EN50366 for compliance testing does not prevent exposures far above the basic restrictions and therefore needs revisions.

To obtain the scientific basis for a sound and reliable compliance test procedure, systematic evaluations of induced currents as a function of human anatomy and field distributions are necessary and recommended.

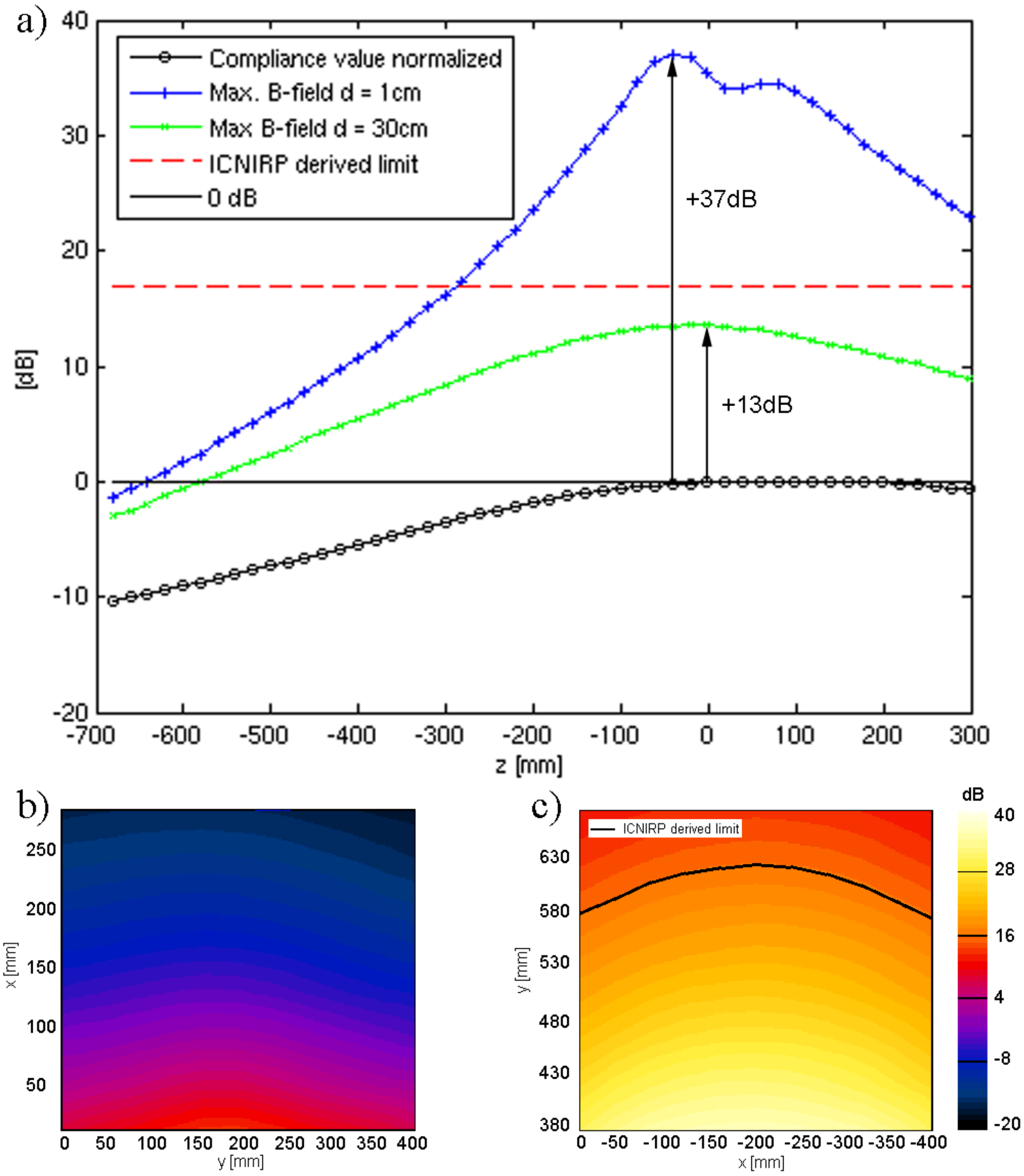


Figure 1: a) Comparison between the compliance value (B-field measured according to EN50366) and the maximum B-field measured in the worst-case scenarios at 1 cm and 30 cm of Appliance 3. b) B-field measured according to EN50366 and c) B-field measured in the worst-case appliance (horizontal plane at height of appliance).

Contents

2 Introduction

2.1 Background

Induction cooking has gained popularity since its introduction in the 1980s. It combines the advantages of traditional gas and electric cooking, i.e., fast heat adjustment, precise cooking temperature control and a glass-ceramic cooking top, allowing easy and fast cleaning. Additionally, the surroundings of the hob barely heat up, thus minimizing the risk of burning. However, this also allows a person to stay in the vicinity of the cooking area, where the magnetic flux density can have large values because of the proximity to the current coils.

Induction cookers generate strong magnetic fields by passing an alternating current (frequencies typically a few tens kHz) through the coils in the hob. When magnetic-material pans are placed on the hob, the magnetic field generates heat in the ferromagnetic cooking vessel due to magnetic hysteresis and induced eddy currents.

Devices emitting electromagnetic fields (EMF) are present in our living environment in ever increasing numbers. This stimulates public concern about possible health effects due to exposure to EMF. Safety concerns about exposure to magnetic stray-fields have arisen, since the fields from the induction cooker cannot be fully shielded and are induced in the close vicinity of the user (e.g., pregnant cook).

Studies by Suzuki and Yamazaki have assessed the magnetic fields with opposite findings. Suzuki [1] reported that the maximum induced currents (numerical dosimetry) in the vicinity of an induction cooker did not exceed the basic restrictions provided by ICNIRP [2]. However, in a recent publication, Yamazaki [3] assessed the magnetic field from an induction cooker hob (1.3 kW) and reported B-field values exceeding the ICNIRP guidelines: B-fields (rms-value) greater than 14μT were measured for the fundamental frequency of 26.1 kHz, whereas the ICNIRP derived limit (general public exposure, 3 to 150 kHz) is only 6.25μT [2].

2.2 Objective

The objective of this study was to assess the exposure that arises during use of induction cooking devices. This was achieved by the detailed evaluations of three devices currently available on the Swiss market (one portable and two built-in appliances):

- First, the B-field exposure was assessed according to the European Norm EN50366 [4].
- Secondly, the worst-case field distributions were determined through measurements with combinations of pots and pans of different sizes, shapes, and materials in single and multi-hob use.
- Third, the adherence of the compliance procedure of the European Norm EN50366 to the basic restrictions of ICNIRP were discussed.

3 Experimental Setup

3.1 Setup Design

In order to find and evaluate the worst-case B-field exposure that arises during the realistic use of induction cookers, the experimental setup shown in Figure 2 has been implemented. It consists of:

- Three induction cooking appliances currently available on the Swiss market (winter 2005/06): one portable and two built-in devices. All three appliances are mounted on a wooden support, allowing measurements in close proximity (see 3.2).
  - Appliance 1: Electrolux GK58TCi (built-in)
  - Appliance 2: Gaggenau CI 261 110 (built-in)
  - Appliance 3: Inducs SH/BA 5000 (portable)
- 16 pots and pans of different sizes, shapes, and materials, including a *standard set of pots* and a *worst-case set of pots* (definition in 3.3).
- The Narda exposure level tester ELT-400 (Narda GmbH, Pfullingen, Germany), used in all measurements of the magnetic flux density (see 3.4).
- The DASY4 dosimetric assessment system from SPEAG (Zurich, Switzerland), used to map the spatial B-field for each device. The software and hardware of the DASY4 system has been extended to also allow 3D-scanning with probes from other manufacturers.

3.2 Induction Cookers

3.2.1 Induction Cookers Available on the Swiss Market

Market review A review of induction cooking equipment available on the Swiss market is presented in Table 1 (as of 1. Dec. 2005). The distinction was made between built-in and portable appliances. The portable appliances typically provide higher power for the hobs, which may correspond to a higher B-field exposure, and a larger variety of designs, control options and accessories. The built-in equipment can be divided into four groups with similar technical data: Miele/Fors, AEG/Electrolux, Bauknecht/IKEA and Siemens/Gaggenau. Only the layout of the hobs and control panel is different. It can be assumed that different brands source modules from the same few OEM (original equipment manufacturers).

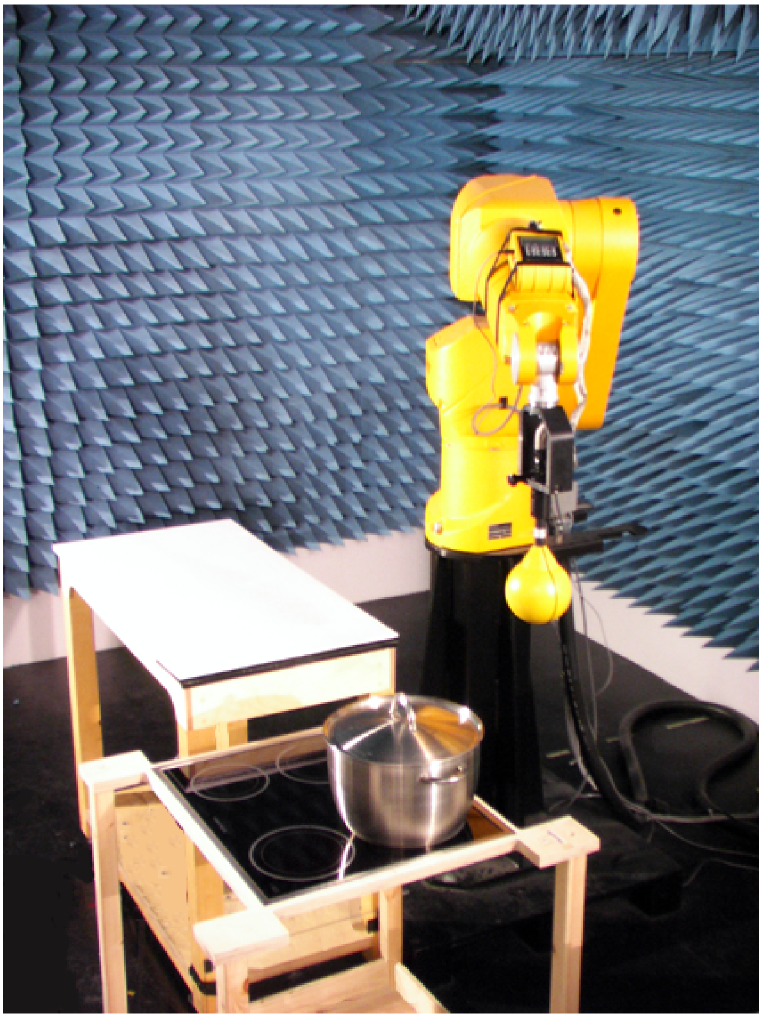


Figure 2: Experimental setup to assess the B-field exposure. The Narda probe ELT-400 is attached on the DASY4 robot system, and the induction cooking appliance is mounted on a wooden support.

Table 1: Selection of induction cooking equipments available on the Swiss market (as of 1. Dec. 2005). Other manufacturers such as Brandt-Fagor, Haier and Maytag are not present on the Swiss induction cooker market. Whirlpool is represented by Bauknecht. This list contains the most widely available equipment but is not complete.

Manufacturer Brand	Model	Rated hob power [kW] (with booster function)				Rated total power (no booster)	Hobs with booster function	Strongest hob location
		Front-left	Front-right	Rear-left	Rear-right			
built-in induction cookers								
Miele	KM492	1.8 (2.3)	1.4	1.8	2.2 (3)	7.2	2	Rear
Fors	SIR60FB	1.4	1.8 (2.3)	2.2 (3)	1.8	7.2	2	Rear
AEG	68001K-in	2.2 (3)	1.8 (2.3)	1.8 (2.3)	1.2 (1.5)	7	4	Front
Electrolux	GK58TCi	2.2 (3)	1.8 (2.3)	1.8 (2.3)	1.2 (1.5)	7	4	Front
Bauknecht	ETPI5640	1.4 (1.9)	1.4 (1.9)	2.2 (3)	1.8 (2.3)	6.8	4	Rear
IKEA	ELDIG HOB V00	1.4	1.8	2.2	1.4	6.8	0	Rear
Siemens	E775501	1.7 (2.5)	2.2 (3.3)	1.7 (2.5)	1.2 (1.8)	6.8	4	Front
Gaggenau	CI 261 110	1.7 (2.5)	2.2 (3.3)	1.7 (2.5)	1.2 (1.8)	6.8	4	Front
V-Zug	GK46TI	(2.5)	(1.8)	(2.5)	(3.2)	7.4	4	Rear
Gaggenau	VI 411-110	(3.5)	-	-	-	3.5	1	Front
portable induction cookers								
Inducs	SH/BA 3500	3.5	-	-	-	3.5	0	Front
Inducs	SH/BA 5000	5.0	-	-	-	5.0	0	Front
Inducs	SH/DU/BA 5000	5.0	5.0	-	-	10.0	0	Front

In Table 1, the maximum rated power of each hob is given without and with the booster function for each model. The total power of the appliance is also provided (sum of the specified maximum power of each hob without booster). The booster function permits the application of additonal power to a specific hob, with the limitation that not all hobs are available for use; otherwise the maximum rated power would be exceeded. Table 1 lists the number of hobs with the booster function available.

built-in equipment characteristics All built-in appliances in Table 1 have four hobs, except the Gaggenau VI 411-110 model, which has a single-hob. The hobs have different sizes, with diameters varying from 10 cm to 23 cm. The appliances have a compact layout (approx. 60 cm width, 55 cm length) without extra warming zones. The surface is a glass-ceramic plate, with an integrated control panel in the front. All built-in appliances in Table 1 require two-phase mains power (230 V and 16 A), and suitable pots are automatically detected. The booster function is available on two or all four hobs or is not available. The booster function is usually labeled *P* (for power) and corresponds to the highest heat setting.

Portable equipment characteristics The characteristics of portable induction cooking appliances are similar to those of built-in equipment. The portable Inducs appliances have one or two hobs, which have a higher rated power than built-in appliances. The Inducs model SH/DU/BA 5000 operates on a three-phase mains power supply.

Comparison and selection of three induction cookers Table 1 facilitates the comparison and selection of three representative appliances. It is expected that the appliances exhibiting the worst-case *B*-field exposure will be those with the highest hob rated power. The position of the strongest hob with respect to the user is also considered and given for each model in Table 1 (front or rear). To perform a worst-case assessment, appliances with the strongest hob in the front were selected.

One portable and two built-in appliances have been selected for experimental evaluation. From groups with similar technical data, only the cheapest was chosen. It has been decided not to follow the initial proposal, that one device shall be as similar as possible to the original cooker used by Yamazaki et al. (domestic induction cooker, 1.3 kW, with a casting pot filled 80 % with water), since it is a much low power device and such devices are not readily available on the Swiss market. The selection is depicted in Figure 3 and includes:

- Appliance 1: Electrolux GK58TCi (built-in)
- Appliance 2: Gaggenau CI 261 110 (built-in)
- Appliance 3: Inducs SH/BA 5000 (portable)

3.2.2 Characteristics of the three selected Induction Cookers

Dimensions and coordinate system The dimensions of the three appliances and the coordinate systems used in the measurements are shown in Figures 4 and 5.

Numbering of the hobs The hobs are numbered as shown in Figure 6. The rated hob power for each appliance is given in Table 1.

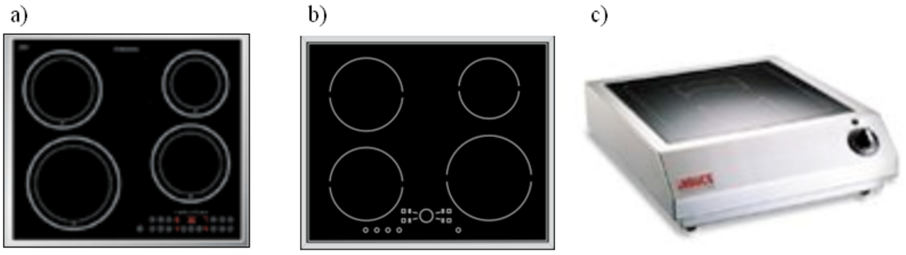


Figure 3: Selected induction cookers. a) appliance 1: Electrolux GK58TCi, b) appliance 2: Gaggenau CI 261 110, and c) appliance 3: Inducs SH/BA 5000.

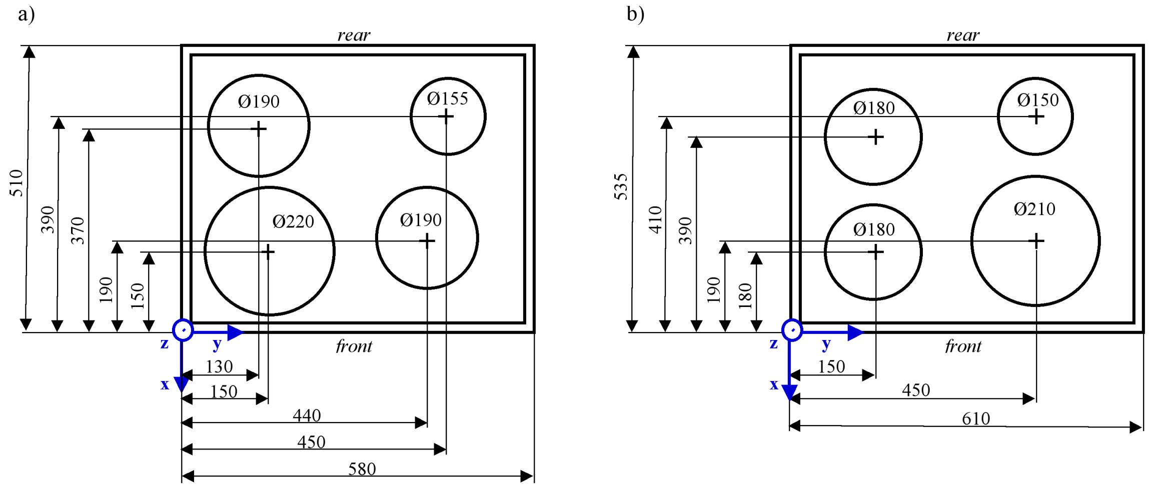


Figure 4: Top view, dimensions (in mm) and coordinate system for a) appliance 1 (Electrolux) and b) appliance 2 (Gaggenau).

Control panel and heat setting

- **Appliances 1 and 2 (Electrolux and Gaggenau, respectively)** The control panel allows heat setting selection varying from 0 to 9 (minimum to maximum power). The booster function (heat setting P) is available for all 4 hobs, but not simultaneously. For appliance 1, the heat setting P is available simultaneously with hobs 1 and 2, or with hobs 3 and 4. For appliance 2, the heat setting P is available for hob 1 if hob 3 is switched off and reciprocally (same for hobs 2 and 4).
- **Appliance 3 (Inducs)** The heat setting varies from 0 to 12 (minimum to maximum power). There is no booster function with appliance 3.

Mounting All three appliances are mounted on 20 mm thick plywood supports allowing close proximity measurements (1 cm on each side). The mounting has been performed according to the manufacturer's specifications. The entire support system base is wooden without any metallic parts in the vicinity of the appliances, thus eliminating the possibility of field distortions.

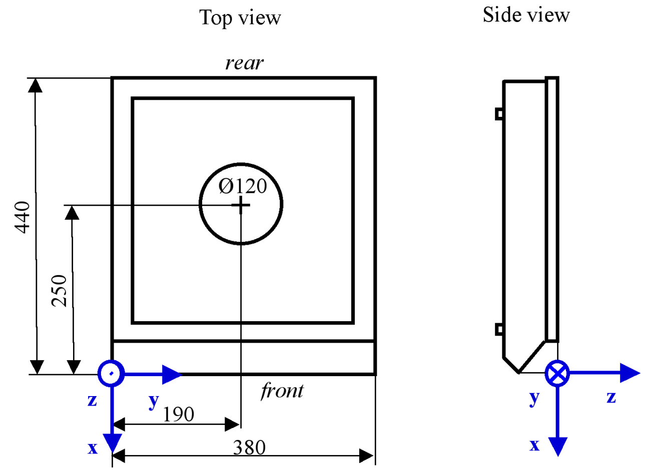


Figure 5: Dimensions (in mm) and coordinate system of appliance 3 (Inducs), top view and side view.

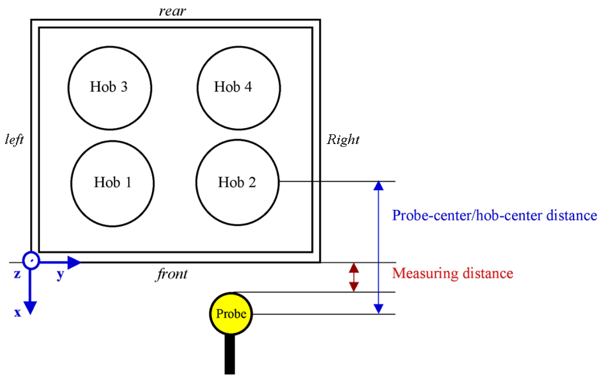


Figure 6: The hobs 1 to 4 correspond, respectively, to the front-left, front-right, rear-left and rear-right hobs. The front, rear, left and right sides of the appliance are indicated, as well as the measuring distance and probe-center/hob-center distance.

The dimensions of the supports and the corresponding pictures are given in Figures 7 and 8, respectively.

Measuring distance and probe-center/hob-center distance The measuring distance, defined as the distance between the surface of the appliance and the closest point of the sensor surface, according to EN50366, will be used. However, the corresponding distance between the probe-center and hob-center is also relevant, since it is directly related to the B-field measured (see Figure 6). Both distances are given in Table 3 for all appliances and hobs.

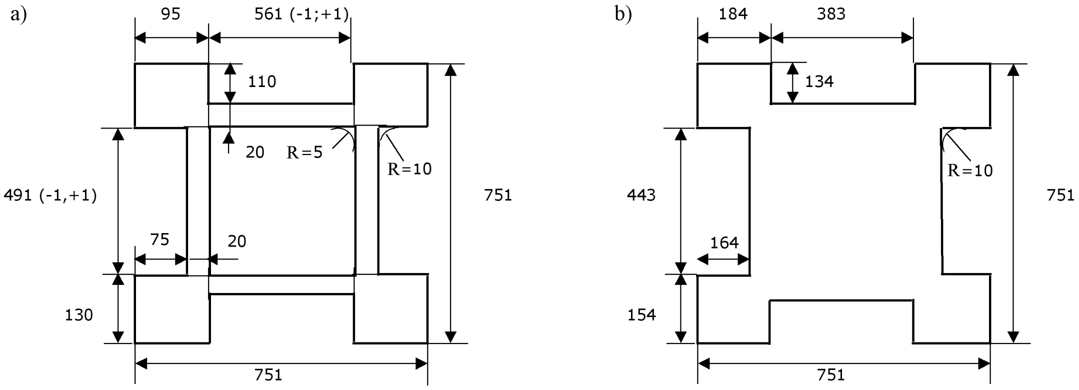


Figure 7: Dimensions of the wooden supports (in mm): a) appliances 1 (Electrolux) and 2 (Gaggenau), and b) appliance 3 (Inducs).

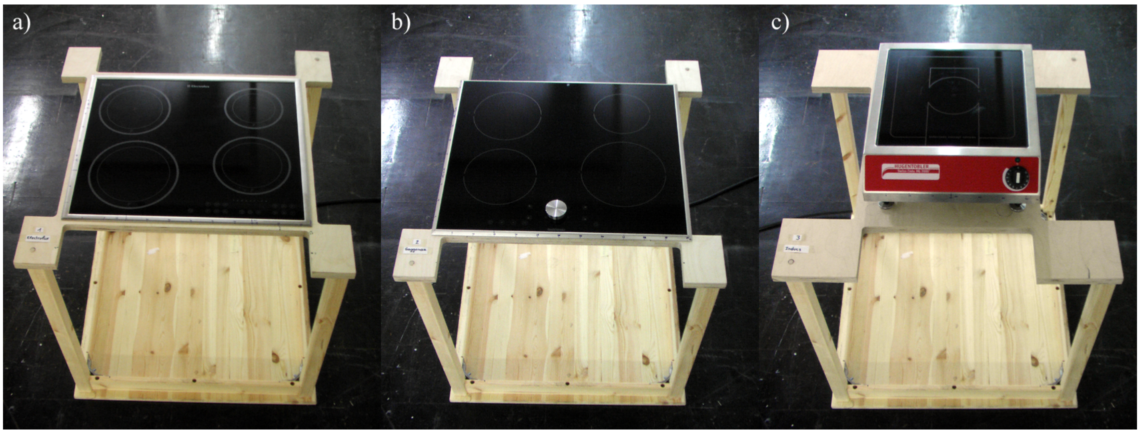


Figure 8: Induction cookers with wooden supports: a) appliance 1 (Electrolux), b) appliance 2 (Gaggenau) and c) appliance 3 (Inducs).

3.3 Pots and Pans

The B-field exposure has been assessed for several new and used pots and pans of different sizes and shapes, as well as various materials. These are depicted in Figure 10.

3.3.1 Norm, Manufacturer Instructions and the Standard Set of Pots

EN50366 test conditions The test conditions for induction hobs given in norm EN50366 specify that standard measurements should be performed using an enameled steel cooking vessel, filled to 50 % of its capacity with tap water. The smallest vessel recommended in the instructions is used. If no recommendations are provided, the smallest standard vessel that covers the marked cooking zone is used.

Manufacturers instructions The hobs diameter of the three appliances are given in Figures 4 and 5. The Inducs manual (appliance 3) states that the minimum diameter for pots and pans is 12 cm without specification of pot thickness. The Electrolux manual (appliance 1) specifies a bottom thickness of 2 to 3 mm for enameled steel pots, and 4 to 6 mm for stainless steel pots, without specification of minimal pot diameter. Instructions concerning suitable pots and pans are given in the manuals of all appliances:

- Only ferromagnetic pans are suitable for induction cooking. They can be made of steel, enameled steel, cast-iron or special stainless steel. Aluminum, copper, brass, glass, ceramics or porcelain pots must not be used. To check whether a pot is suitable, the use of a magnet is suggested: If it sticks the pot is suitable for induction cooking.
- Cooking with an empty pan should be avoided. The hob immediately switches off in the case of overheating. This function is available on all three appliances.
- Pots and pans must be centered on the hobs to avoid nonuniform heating.
- The pot must have a minimum diameter which is related to the hob dimension. If the pot is too small or of unsuitable material, the hob will not switch on. This function is available on all three appliances. It is recommended to always choose a properly sized pot for the quantities of food to save energy.
- Metallic objects such as cans, utensils, jewelry, cutlery, watches, aluminum foil paper, and lids should not be put on the hobs to avoid the danger of burning.

Standard set of pots In order to comply with the test conditions specified in EN50366, a *standard set of pots* has been defined (see Figure 9). It corresponds to the pots 3, 14a, 14b and 13, with bottom diameters of 22 cm, 18 cm, 18 cm and 14.5 cm, respectively. These pots correspond to the smallest standard vessel that covers the marked cooking zone for all three appliances. The standard pots are not of enameled steel but of stainless steel, since stainless steel cooking vessels are sold in the largest volume on the Swiss market.

Figure 9: Standard set of pots.

3.3.2 Worst-Case Set of Pots

However, despite the manufacturer instructions, users do not always follow the included recommendations, and not everyone operating an induction cooker has read the manual. When consumers buy a new induction cooking appliance, they are likely to continue using old pans if they appear to work, despite not being perfectly adapted for induction cooking. In order to perform a worst-case B-field exposure and to select a worst-case set of pots, 16 pots and pans were assessed (Figure 10). Their characteristics are given in Table 2.

Figure 10: Pans, frying-pans and pots used during the experiments to define the worst-case set of pots.

Table 2: Characteristics of pans, frying-pans and pots used in the experiments.

Pot	Description	Manufacturer / Distributor	Material	Dimensions Bottom Diameter [cm]	Height [cm]	Capacity [l]	Lid	New
1	frying-pan	IKEA	stainless steel, aluminum	22	5	2	no	yes
2	small saucepan	IKEA	stainless steel, aluminum	15	10	2	yes	yes
3	large pot	IKEA	stainless steel, aluminum	22	19	10	yes	yes
4	saucepan, bottom not flat	2^{nd} hand shop	stainless steel,	18	10	2	no	no
5	non-paramagnetic Saucepan	2^{nd} hand shop	non-paramagnetic stainless	18	10	2	no	no
6	large enameled pot	2^{nd} hand shop	enameled steel	18	11	3	no	no
7	small enameled pot	2^{nd} hand shop	enameled steel	14	8	1.5	yes	no
8	small enameled pot	2^{nd} hand shop	enameled steel	14	12	1.5	no	no
9	wok	2^{nd} hand shop	steel	12	9	4	no	no
10	cast-iron pot	Migros	cast-iron	17	11	3.5	yes	yes
11a	small pot	Migros	stainless steel	16	9	2	yes	yes
11b	small pot	Migros	stainless steel	16	9	2	yes	yes
12	large pot	Migros	stainless steel	22	11	5	yes	yes
13	small pot	IKEA	stainless steel	14.5	13	2.5	yes	yes
14a	medium pot	IKEA	stainless steel	18	14.5	4.5	yes	yes
14b	medium pot	IKEA	stainless steel	18	14.5	4.5	yes	yes

Table 3: Measuring distances and corresponding probe-center/hob-center distances. According to EN50366, the measuring distance is the distance between the surface of the appliance and the closest point of the sensor surface. The front, rear, left and right sides of the appliances and the hob numbering are shown in Figure 6.

appliance 1 (Electrolux)	front side				rear side				left side				right side			
hob	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
measuring distance [mm]	10				10				10				10			
dist. probe/hob center [mm]	222.5	262.5	442.5	462.5	432.5	392.5	212.5	192.5	222.5	512.5	202.5	522.5	502.5	212.5	522.5	202.5
measuring distance [mm]	300				300				300				300			
dist. probe/hob center [mm]	512.5	552.5	732.5	752.5	722.5	682.5	502.5	482.5	512.5	802.5	492.5	812.5	792.5	502.5	812.5	492.5

appliance 2 (Gaggenau)	front side				rear side				left side				right side			
hob	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
measuring distance [mm]	10				10				10				10			
dist. probe/hob center [mm]	252.5	262.5	462.5	482.5	427.5	417.5	217.5	197.5	222.5	522.5	222.5	522.5	532.5	232.5	532.5	232.5
measuring distance [mm]	300				300				300				300			
dist. probe/hob center [mm]	542.5	552.5	752.5	772.5	717.5	707.5	507.5	487.5	512.5	812.5	512.5	812.5	822.5	522.5	822.5	522.5

appliance 3 (Inducs)	front side	rear side	left side	right side
hob	1	1	1	1
measuring distance [mm]	10	10	10	10
dist. probe/hob center [mm]	322.5	262.5	262.5	262.5
measuring distance [mm]	300	300	300	300
dist. probe/hob center [mm]	612.5	552.5	552.5	552.5

Worst-case set of pots A *worst-case set of pots* has been selected (see Figure 11), composed of pots 8, 7, 13 and 2 with bottom diameters of 14 cm, 14 cm, 14.5 cm and 15 cm, respectively.

Figure 11: Worst-case set of pots.

3.4 B-field Narda Sensor ELT-400

The magnetic flux density (B-field) was measured using the Narda exposure level tester ELT-400 (see Figure 12).

Figure 12: Narda exposure level tester ELT-400.

The probe is especially designed for investigating the magnetic field produced by household equipment and other electrical devices. The DASY4 system was extended to enable use with the Narda probe ELT-400. This involved mechanical, electrical and software modifications. The reference test method described in EN50366 is implemented in the Narda probe, and the measured B-field is given in [μT], or as a percentage of the ICNIRP guideline [2]. The 3D-sensor system covers the frequency range from 1-30 Hz to 400 kHz. The B-field is measured using three orthogonal coils with a common center point (allowing isotropic measurement). The cross sectional area is 100 cm^2 (standard-compliant), and the probe's external diameter is 125 mm. The signal voltages in the coils are digitized and evaluated by a digital signal processor (DSP), which calculates in real-time the root-mean-square (rms) value of the B-field, according to EN50366 [4]. The rms-value of the magnetic flux density B is calculated from the rms-values of each of the three measurement axes (B_x, B_y and B_z) according to Equation (1).

$$B = \sqrt{B_x^2 + B_y^2 + B_z^2} \tag{1}$$

The measurement time interval is 250 ms. The rms-value, given in [μT], is continuously integrated over four intervals, and the integration time of the rms calculation is fixed at 1 s. The Narda ELT-400 probe can also operate as an active probe, using the three separate, analog signals corresponding to the three spatial axes x, y, and z. Connecting it to an external oscilloscope or spectrum analyzer allows temporal and spectral measurements.

In this project, the Narda probe ELT-400 is used in *field strength mode*, which is a measurement of the magnetic flux density based on broadband evaluation of the signal, for the bandwidth 30 Hz to 400 kHz. The measurement uncertainty of the instrument is ±4 % (50 Hz to 120 kHz). The frequency response for the selected bandwidth limits 30 Hz and 400 kHz is −3 dB ±1 dB. The settings selected are given in Table 4. The intrinsic noise is 70 nT and 320 nT for the *low* and *high* range settings, respectively.

Table 4: Settings of the Narda probe ELT-400.

Mode	320 μT	
Range	Low	High
Overload Limit[a]	32 μT	320 μT
Nominal Measurement Range[b]	2 μT	20 μT
Intrinsic noise (rms)	70 nT	320 nT

[a] Maximum measurable rms-value of a sine wave.

[b] Maximum measurable rms-value of a signal of any shape with a crest factor (peak value/rms-value) of less than 22.

4 Evaluation of Measurement System

4.1 Sensor Characterization

Helmholtz coil The uncertainty of the Narda instrument was evaluated using the Helmholtz coil, designed to test the T-coil compatibility of mobile phones (ANSI63.19). It is comprised of a pair of identical circular magnetic coils (diameter 284.8 mm) that are coaxially aligned and separated by a distance equal to the radius of the coil. Each coil carries an equal electrical current. The cylindrical region extending between the centers of the two coils and approximately 1/5 of their diameters has a magnetic field with high spatial uniformity. The Helmholtz coil is connected to the waveform generator (Agilent 33120A). The corresponding electronic circuit is given in Figure 13.

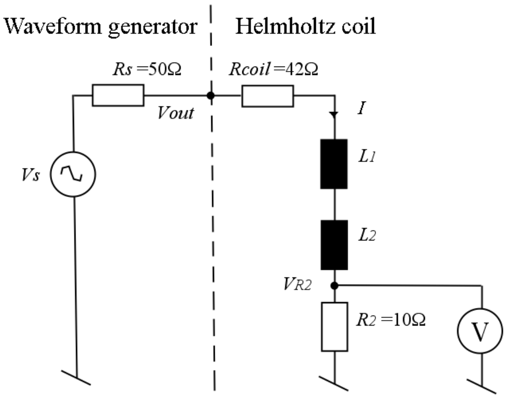


Figure 13: Electronic circuit of the Helmholtz coil connected to the waveform generator (Agilent 33120A).

The current I in the Helmholtz coil and the voltage V_{out} at the output of the waveform generator are given in Equations (2) and (3), respectively.

$$I = \frac{V_{R_2}}{R_2} = \frac{V_{out}}{R_{coil} + R_2} \tag{2}$$

$$V_{out} = V_s \frac{R_{coil} + R_2}{R_s + R_{coil} + R_2} \approx \frac{1}{2} V_s \tag{3}$$

In the frequency domain, the current $I(\omega)$ in the Helmholtz coil is given in Equation (4), where $I(\omega) = Ie^{j\omega t}$ and $V_{out}(\omega) = V_{out}e^{j\omega t+\alpha}$ are the current and voltage in the complex domain, $\omega = 2\pi f$ is the angular velocity and f is the frequency. The cut-off frequency is given by $f_c = R_2/2\pi(L_1 + L_2)$ and is here $f_c \approx 20\,\text{kHz}$ for the Helmholtz coil. The frequency response of the coil is shown in Figure 14 b).

$$I(\omega) = \frac{V_{out}(\omega)}{R_2 + j\omega(L_1 + L_2)} \tag{4}$$

An approximation of the B-field at the center point of the Helmholtz coil system is given in Equation (5), where R is the radius ($R_{average} = 142.4\,\text{mm}$), N is the number of turns in each coil ($N = 20$) and I is the current in the coils [6].

$$B = (\frac{4}{5})^{3/2}\frac{\mu_0 NI}{R} \tag{5}$$

The generated B-fields in the Helmholtz coil are $8.6\,\mu$T and $0.86\,\mu$T when applying $V_{out} = 10\,\mathrm{V}_{pp}$ and $1\,\mathrm{V}_{pp}$ (peak-to-peak), in the frequency range corresponding to a flat response.

Frequency response The specifications of the Narda probe ELT-400 indicate a flat frequency response for the frequency range from 30 Hz to 400 kHz. To validate this, the experimental setup shown in Figure 15 was used. The probe is at a fixed position in the center of the Helmholtz coil, and the waveform generator applies a sinusoidal voltage, with the frequency stepwise increased from 1 Hz to 800 kHz (amplitude $10\,\mathrm{V}_{pp}$). The frequency response of the Narda probe ELT-400 is shown in Figure 14.

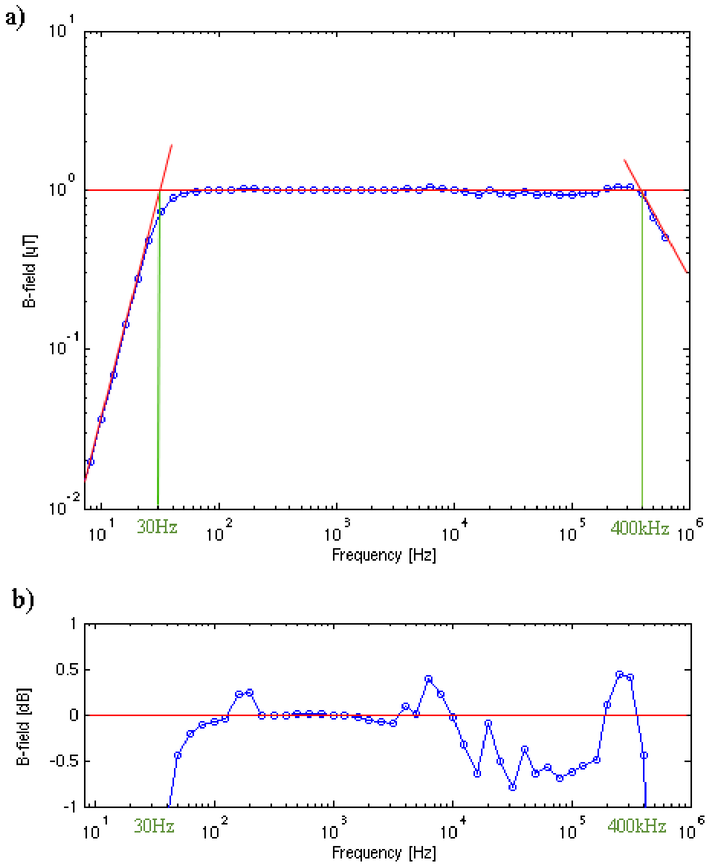


Figure 14: a) Narda probe ELT-400 frequency response, calculated from the frequency responses of the Narda probe ($\omega_{c_1} = 30$ Hz and $\omega_{c_2} = 400$ kHz) and the Helmholtz coil ($\omega_{c_3} = 20$ kHz), as well as the frequency responses of the Helmholtz coil system. b) Deviation from the flat frequency response between 30 Hz and 400 kHz in [dB].

The combined frequency response of the Narda probe ($\omega_{c_1} = 30$ Hz and $\omega_{c_2} = 400$ kHz) and the Helmholtz coil ($\omega_{c_3} = 20$ kHz) was measured using the Narda probe ELT-400. The frequency response of the Helmholtz coil system was then assessed by measuring V_{R2} as a function of the frequency (see Figure 13). The frequency response of the Narda probe ELT-400 was calculated from those two measurements. As given in the specifications, the cut-off frequencies for the Narda probe ELT-400 are around 30 Hz and 400 kHz, and the frequency response is flat between those frequencies; the error is smaller than ±0.8 dB. The error in [dB] was calculated using the Equation (6):

$$Error[dB] = 20\log(B/B_{average}) \tag{6}$$

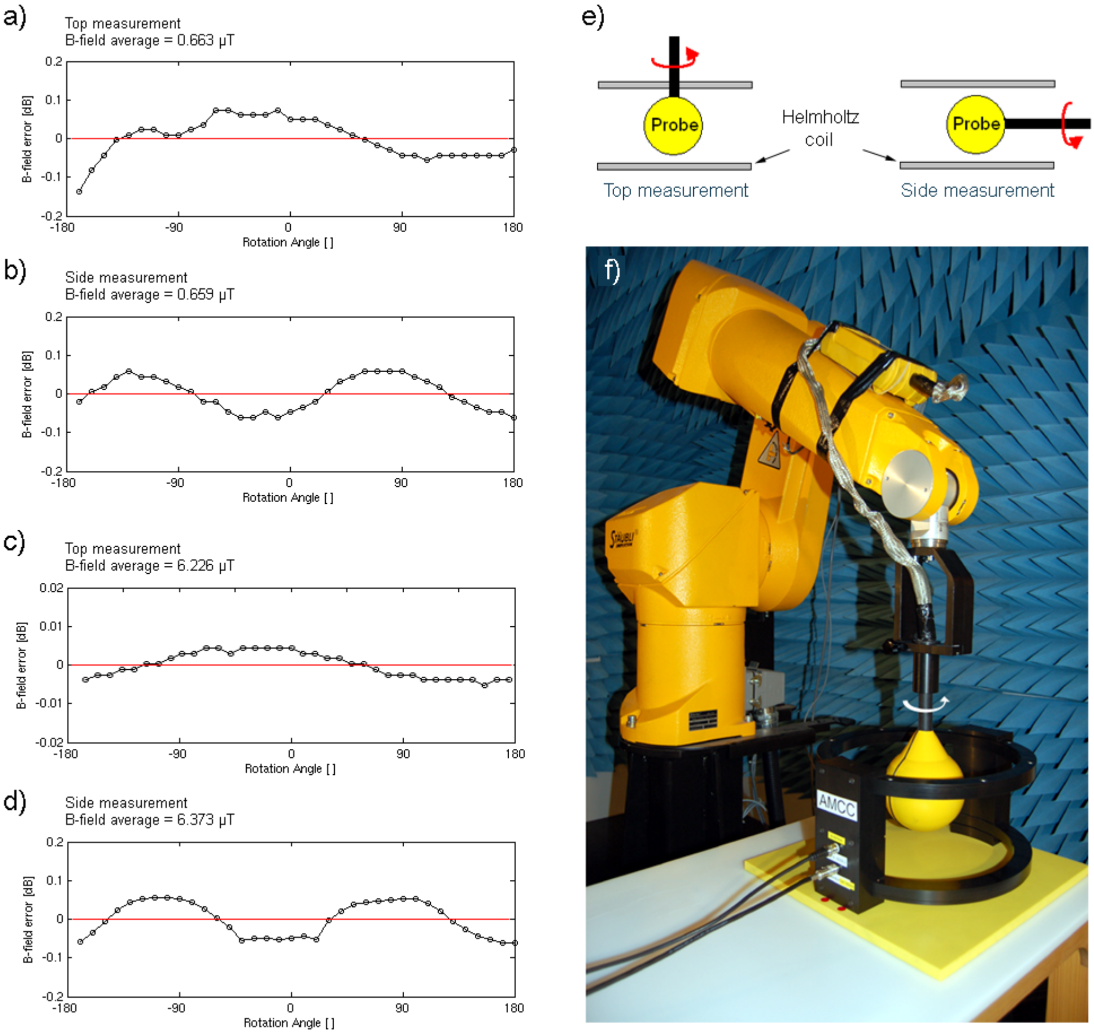


Figure 15: Spherical isotropy of the Narda probe ELT-400. The probe was attached to the DASY4 robot arm and centered in the Helmholtz coil. A waveform generator (Agilent 33120A) applied a sinusoidal voltage (frequency 20 kHz) to the Helmholtz coil. The B-field values were recorded while rotating the probe around its z-axis. Error in [dB] of the B-field measured when applying in the coil a) 1 V_{pp}, top measurement, b) 1 V_{pp}, side measurement, d) 10 V_{pp}, top measurement, and b) 10 V_{pp}, side measurement; e) diagram of top measurement and side measurement; f) measurement setup of the spherical isotropy of the Narda probe.

Spherical isotropy The experimental setup shown in Figure 15 f) was used to evaluate the spherical isotropy of the Narda probe ELT-400. The probe rotates around its vertical z-axis, and the B-field is measured as a function of the probe angle of rotation (from -180° to 180°). The measurements are performed on the top and at the side of the Helmholtz coil (see Figure 15 e)). The uncertainty due to deviations from spherical uncertainty has been determined by the worst-case values assuming rectangular distribution, i.e., $\pm\, 0.2\,\mathrm{dB}/\sqrt{3}$.

Linearity In order to check the linearity of the probe, a sinusoidal voltage was applied to the Helmholtz coil, with the amplitude varying between $0.1\,\mathrm{V}_{pp}$ and $10\,\mathrm{V}_{pp}$ (frequency of 20 kHz). The experimental setup shown in Figure 15 f) was used. The probe was centered in the Helmholtz coil. The B-field was measured as a function of the voltage applied to the coil as shown in Figure 16. The linearity is very good for B-fields greater than $0.3\,\mu\mathrm{T}$, which corresponds to a deviation from linear response $< \pm 0.05\,\mathrm{dB}$. The error increases for lower fields and equals 2.8 dB for B-fields of $\approx 0.06\,\mu\mathrm{T}$ ($0.1\,\mathrm{V}_{pp}$).

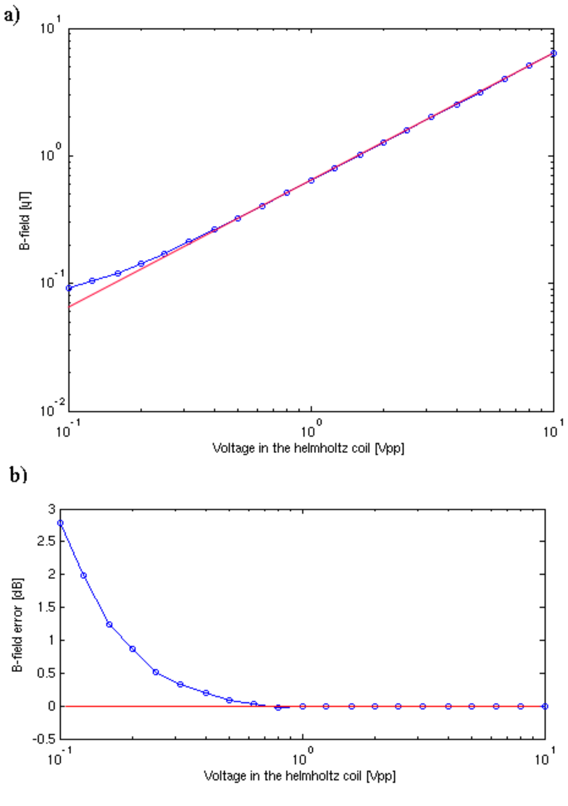


Figure 16: Linearity of the Narda probe ELT-400. a) The B-field is measured for amplitudes between $0.1\,\mathrm{V}_{pp}$ and $10\,\mathrm{V}_{pp}$ (frequency 20 kHz). b) Deviation from linear response in [dB].

4.2 Time- and Frequency-Domain Characterization of the Induction Cookers

4.2.1 Time-Domain Characterization

Measurements The alternating magnetic fields generated by the induction cookers were measured with the Narda probe ELT-400. The analog output signals of the probe were recorded with a digital oscilloscope (Agilent 54622D mixed signal oscilloscope). The B-fields were measured in front (measuring distance 1 cm) of the largest hobs: hobs 1, 2 and 1 for appliances 1, 2 and 3, respectively. For each experiment the standard pot 3 with lid was centered on the hob and filled with 3 liters of tap water. The time-domain signals corresponding to appliances 1, 2 and 3 are given in Figures 17, 18 and 19, respectively.

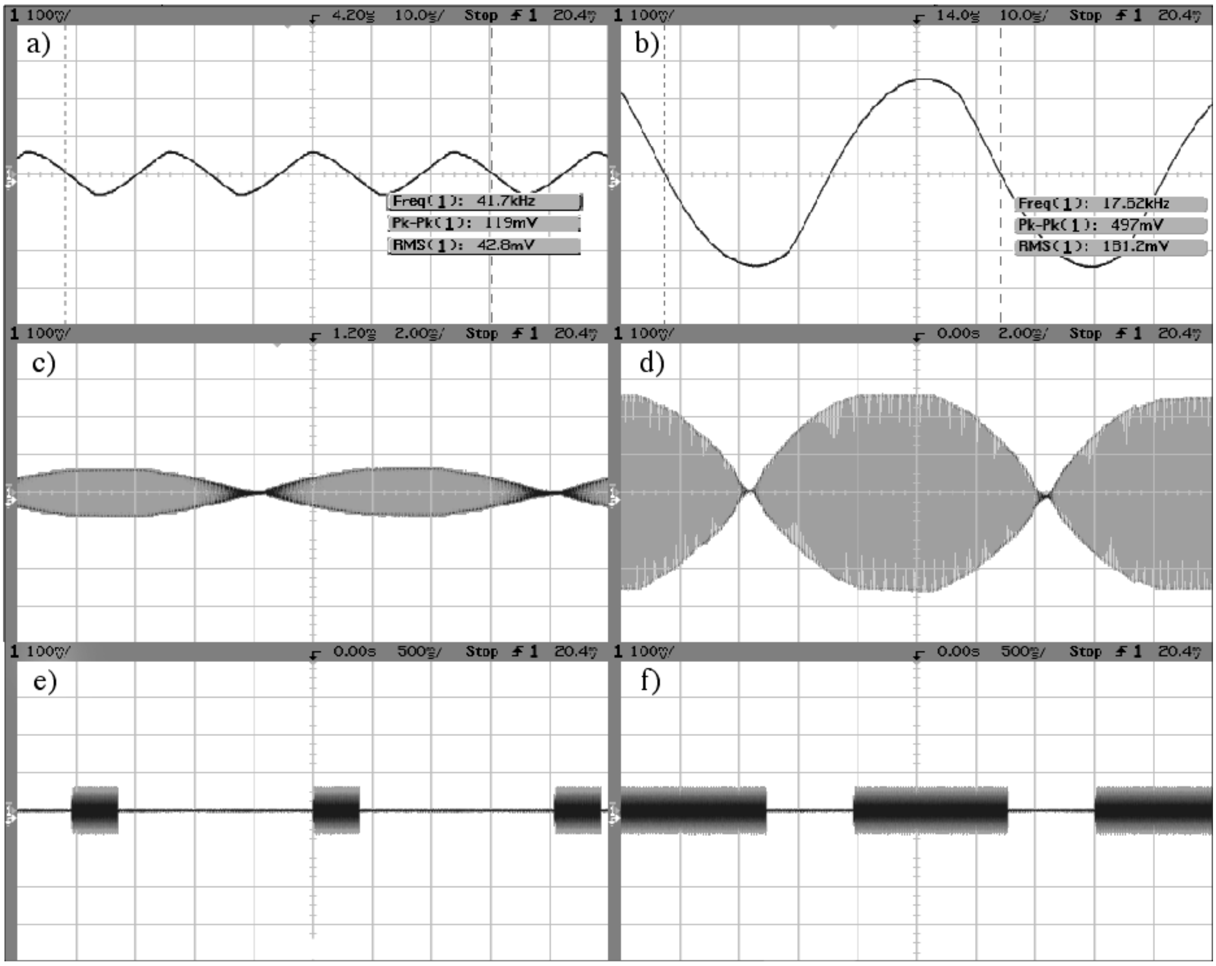


Figure 17: **Time-domain signals of the alternating magnetic fields generated by appliance 1.** Graphs a) and b) correspond to the heat settings 4 and P. The fundamental signal frequencies are, respectively, 41.7 kHz and 17.5 kHz. The signal rms-value increases approximately by a factor of 5 for heat settings from 4 to P. Graphs c) and d) correspond to the heat settings 4 and P and show a signal envelope with a frequency of 100 Hz that remains constant for all heat settings. Graphs e) and f) correspond to the heat settings 1 and 3. For heat settings 1 to 4, the signal is pulse-width modulated, with a frequency of 0.5 Hz.

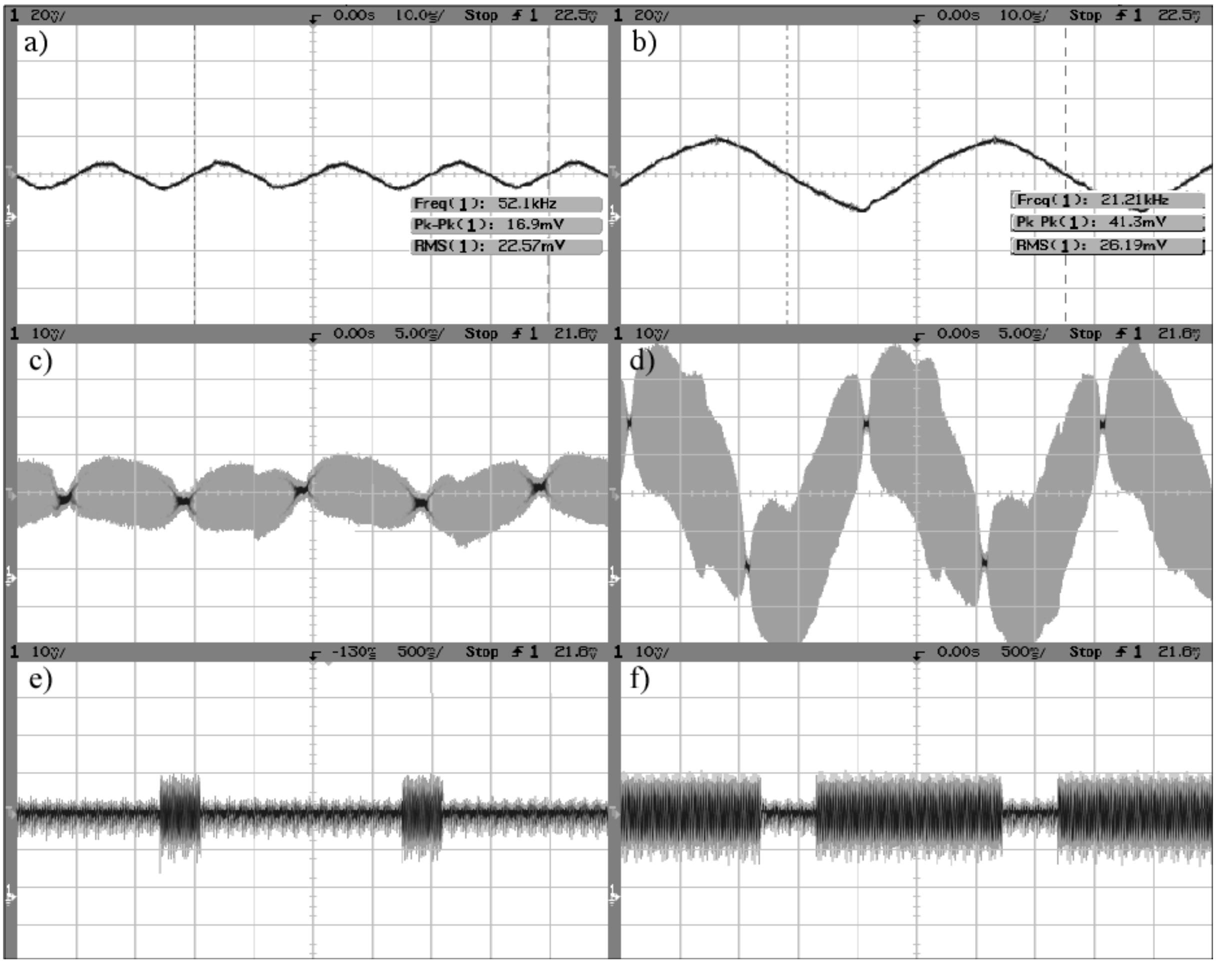


Figure 18: **Time-domain signals of the alternating magnetic field generated by appliance 2.** Graphs a) and b) correspond to the heat settings 4 and P. The fundamental signal frequencies are, respectively, 52.1 kHz and 21.2 kHz. The signal rms-value increases approximately by a factor of 2.5 for heat settings from 4 to P. Graphs c) and d) correspond to the heat settings 4 and P and show a signal envelope with a frequency of 100 Hz that remains constant for all heat settings; d) also shows a 50 Hz component. Graphs e) and f) correspond to the heat settings 1 and 4. For heat settings 1 to 4, the signal is pulse-width modulated, with a frequency of 0.5 Hz.

Discussion The two built-in appliances and the portable appliance present similar characteristics. The signal rms-value increases with the heat setting for all three appliances. As shown in Figures 17 a) and b), 18 a) and b) and 19 a) and b), the rms-value increases approximately by a factor of 5, 2.5 and 4 when the heat setting varies from the lowest to the highest values, for appliances 1, 2 and 3, respectively. At the opposite, the frequency of the signal decreases when the heat setting increases (see Table 5). Figures 17 a) and b), 18 a) and b), and 19 a) and b) also show that the shape of the signal changes for different heat settings. For all three appliances, the signal shape is a triangle at the lowest heat setting and changes into a sinusoidal at the highest heat setting. Figures 17 c and d), 18 c) and d), and 19 c and d) display the signals envelopes. The envelope frequency (100 Hz, 100 Hz and 300 Hz for appliances 1, 2 and 3,

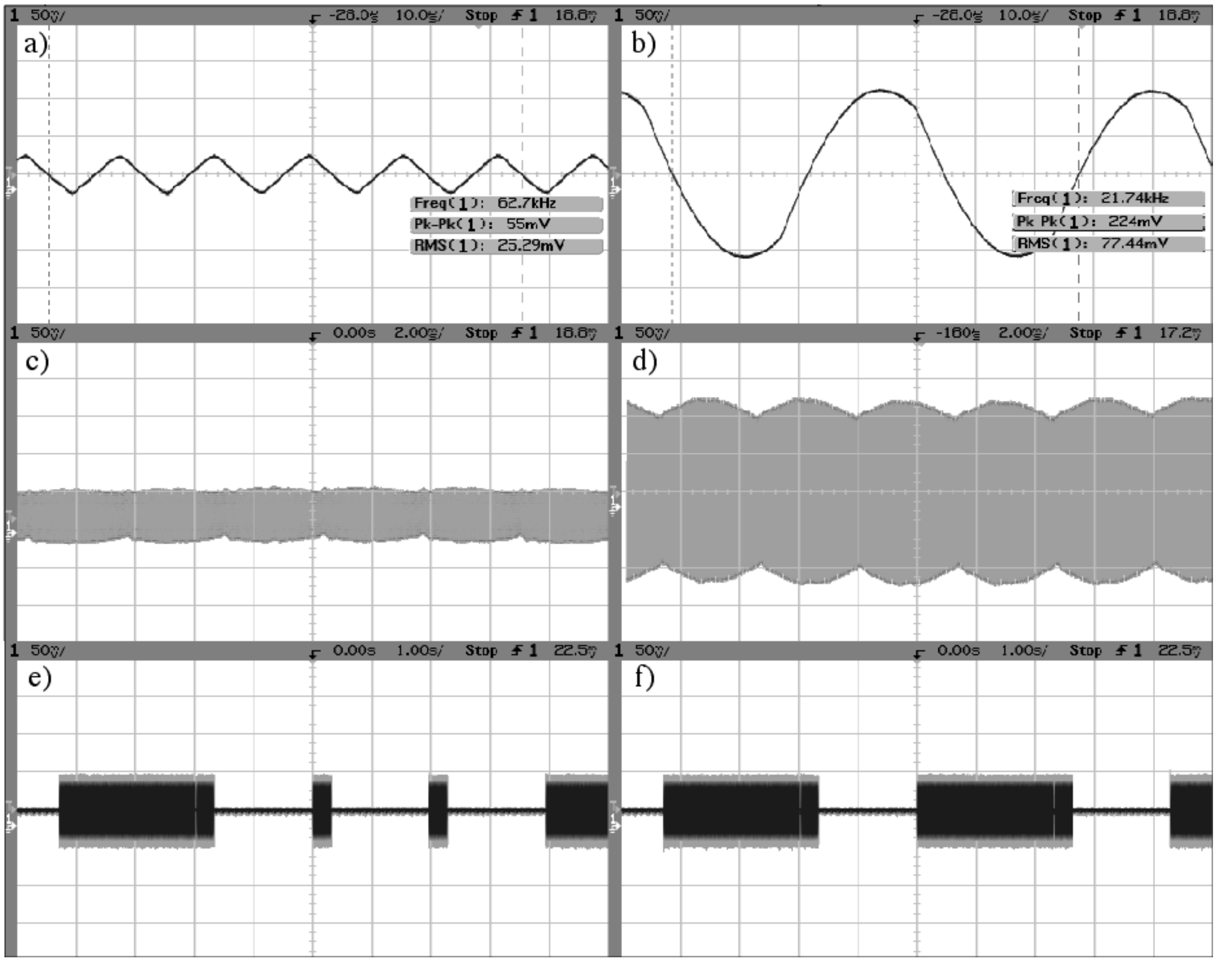


Figure 19: **Time-domain signals of the alternating magnetic field generated by appliance 3.** Graphs a) and b) correspond to the heat settings 4 and 12. The fundamental signal frequencies are 62.7 kHz and 21.7 kHz, respectively. The signal rms-value increases approximately by a factor of 4 for heat settings from 4 to 12. Graphs c) and d) correspond to the heat settings 6 and 10 and show a signal envelope with a frequency of 300 Hz that remains constant for all heat settings. Graphs e) and f) correspond to the heat settings 1 and 3. For heat settings 1 to 4, the signal is pulse-width modulated, with a frequency of approximately 0.5 Hz.

respectively), does not depend on the heat setting (see Table 5). It is assumed that the 100 Hz envelope component is caused by the power supply operating from a single-phase 50 Hz mains, and the 300 Hz component by the three-phase power supply. As shown in Figures 17 e) and f), 18 e) and f), and 19 e) and f), the signal is pulse-width modulated for all three appliances and at the heat settings 1 to 4. The duty cycles (ratio of time on to total cycle time) are given in Table 6.

4.2.2 Frequency-Domain Characterization

The determination of the spectral content of the *B*-field in the frequency range from 10 Hz to 400 kHz was performed with the Narda probe ELT-400 (analog signal output) connected to a

Table 5: Signal and envelope modulation frequency of appliances 1, 2 and 3 for the heat settings 4 and P or 12.

	signal frequency [kHz]		envelope frequency [Hz]	pulse-width modulation frequency [Hz]
heat setting	4	P or 12	4 to max. (P or 12)	1 to 4
appliance 1	42	18	100	0.5
appliance 2	52	21	100	0.5
appliance 3	63	22	300	0.5

Table 6: Duty cycle of appliances 1, 2 and 3 for heat settings 1 to 4, where the signal is pulse-width modulated (no pulse-width modulation for higher settings).

	duty cycle [%]				
heat setting	1	2	3	4	5
appliance 1	20	35	65	95	100
appliance 2	15	30	55	75	100
appliance 3	40	60	60	100	100

spectrum analyzer (Rohde & Schwarz FSP30). The signals were measured at the front side of the appliances for each hob with a measuring distance of 1 cm. For each experiment the standard pot 3 with lid was centered on the hob and filled with 3 liters of tap water.

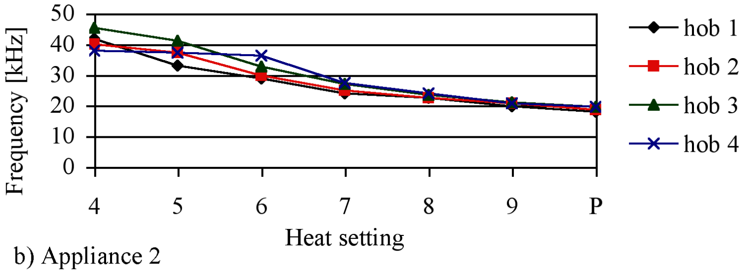
Dependency of the signal frequency on the heat setting for each hob The signal frequencies of all hobs were measured for different heat settings (see Figure 20). As shown in Figures 17, 18 and 19, the frequency decreases when the heat setting increases. The frequency ranges are 18−45 kHz, 21−52 kHz and 22−63 kHz for appliances 1, 2 and 3, respectively. The electronic schemes of the appliances were not provided, and the appliances were not opened. However, in order to explain why the signal frequency decreases for higher heat settings, a simple circuit comprised of a coil L, a series resistor R and a AC voltage source U is considered. The B-field increases with the AC current in the coil. The current in the coil is given by $I(\omega) = V(\omega)/(R + j\omega L)$, where $I(\omega) = Ie^{j\omega t}$ and $V(\omega) = Ve^{j\omega t+\alpha}$ are the current and voltage in the complex domain, and $\omega = 2\pi f$ is the angular velocity. If R, L and V are fixed, the current in the coil I is proportional to $1/f$ (for $\mid \omega L \mid\gg R$).

Harmonics contribution Figure 21 shows the power spectral distribution of the B-field emitted by appliances 1, 2 and 3 for frequencies up to 400 kHz. This frequency range corresponds to the Narda probe bandwidth (30 Hz−400 kHz). The ratio between the fundamental and the harmonics peaks is calculated using Equation (7):

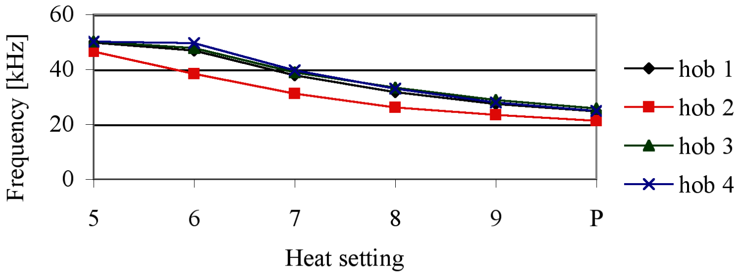
$$\frac{P_{1[mW]}}{P_{2[mW]}} = 10^{\frac{P_{1[dB]}-P_{2[dB]}}{10}} \tag{7}$$

where $P_{1[dB]} - P_{2[dB]}$ is the difference in [dB] between the fundamental and harmonic peaks (power spectrum), and $P_{1[mW]}/P_{2[mW]}$ is the corresponding ratio. The contribution of the

a) Appliance 1



b) Appliance 2



c) Appliance 3

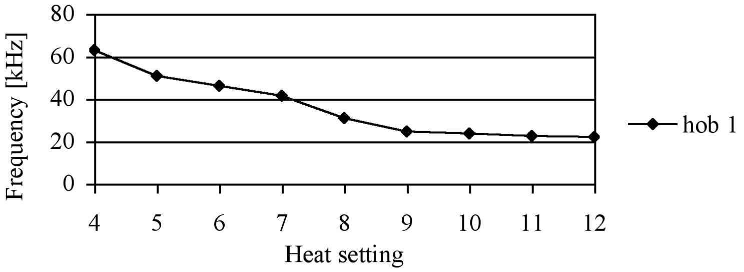


Figure 20: Dependency of the signal frequency on the heat setting. Graphs a), b) and c) correspond to appliances 1, 2 and 3, respectively.

harmonics is calculated for appliances 1, 2 and 3 in Tables 7, 8 and 9, respectively. These Tables show that the contribution in terms of power of all harmonics does not exceed 1 %, 2.5 % and 1.8 % of the fundamental signal for appliances 1, 2 and 3, respectively.

The total harmonics contribution is also given in terms of *B*-field weighted with the frequency f, which is more meaningful for evaluating the contribution to the induced current J in the body (see Chapter 7). If P_{fi} (in [%]) is the contributions in term of power of the harmonics at the frequencies $f_i = 3f, 5f$, etc., the induced current is proportional to:

$$J \propto f_1\sqrt{P_{f1}} + f_2\sqrt{P_{f2}} + ... \propto f(3\sqrt{P_{3f}} + 5\sqrt{P_{5f}} + ...) \propto f\sum_i i\sqrt{P_{if}} \tag{8}$$

4.2.3 *B*-Field Exposure Dependency on the Heat Settings

As shown in Figure 22 a), for appliance 1, the *B*-field exposure increases linearly for higher heat settings. Figures 22 b) and 22 c) show that this dependency follows a second and fourth order polynomial for appliances 2 and 3, respectively.

Table 7: Appliance 1, Calculated harmonics contribution in [%], in terms of power.

Heat setting		4	5	6	7	8	9	P
Fundamental frequency f [kHz]		41.7	33.0	28.8	24.0	22.5	19.8	18.0
Contribution of the harmonics [%]	$3f$	0.8	0.5	0.5	0.4	0.3	0.3	0.3
	$5f$	0.08	0.05	0.06	0.05	0.04	0.03	0.03
	$7f$	0.03	0.02	0.01	0.01	0.008	0.008	0.005
	$9f$	0.006	0.008	0.006	0.004	0.003	0.003	0.003
	$11f$	-	0.003	0.003	0.003	0.002	0.001	0.001
	$13f$	-	-	0.0016	0.0016	0.001	0.0008	0.0005
	$15f$	-	-	-	0.0008	0.0008	0.0005	0.0004
	$17f$	-	-	-	-	0.0005	0.0003	0.0003
	$19f$	-	-	-	-	-	0.0003	0.0002
Total in terms of power [%]		0.916	0.581	0.5806	0.4694	0.3553	0.3439	0.3404
$J \propto \sum_i i\sqrt{P_{if}}$ [%]		5.91	4.93	4.88	4.37	3.76	3.52	3.52

Table 8: Appliance 2, Calculated harmonics contribution in [%], in terms of power.

Heat setting		4	5	6	7	8	9	P
Fundamental frequency f [kHz]		50.1	46.5	39.4	31.2	26.1	23.4	21.30
Contribution of the harmonics [%]	$2f$	-	-	-	0.05	0.03	0.07	0.05
	$3f$	1.6	0.4	0.7	0.8	0.6	1.4	2.0
	$4f$	-	-	-	-	-	0.03	0.02
	$5f$	-	-	-	-	0.1	0.2	0.3
	$6f$	-	-	-	-	-	-	-
	$7f$	-	-	-	-	-	-	0.05
	$8f$	-	-	-	-	-	-	-
Total in terms of power [%]		1.6	0.4	0.7	0.85	0.73	1.7	2.42
$J \propto \sum_i i\sqrt{P_{if}}$ [%]		3.78	1.19	2.55	3.12	4.51	7.13	9.32

Table 9: Appliance 3, Calculated harmonics contribution in [%], in terms of power.

Heat setting		4	5	6	7	8	9	10	11	12
Fundamental frequency f [kHz]		62.9	50.8	46.0	41.3	30.9	24.7	23.5	22.6	22
Contribution of the harmonics [%]	$3f$	1.3	1.3	1.3	1.6	1.3	0.6	0.5	0.4	0.3
	$5f$	0.2	0.2	0.2	0.1	0.2	0.1	0.1	0.08	0.08
	$7f$	-	0.03	0.05	0.05	0.03	0.03	0.02	0.03	0.03
	$9f$	-	-	-	0.02	0.02	0.004	0.008	0.01	0.02
	$11f$	-	-	-	-	0.01	0.002	0.002	0.004	0.005
	$13f$	-	-	-	-	0.003	0.002	0.0008	0.001	0.002
	$15f$	-	-	-	-	-	0.001	0.0006	0.0004	0.0008
	$17f$	-	-	-	-	-	-	0.0005	0.0003	0.0004
Total in terms of power [%]		1.5	1.53	1.55	1.77	1.563	0.739	0.6319	0.5257	0.4382
$J \propto \sum_i i\sqrt{P_{if}}$ [%]		5.60	6.60	6.92	8.39	9.57	7.38	7.11	7.15	7.64

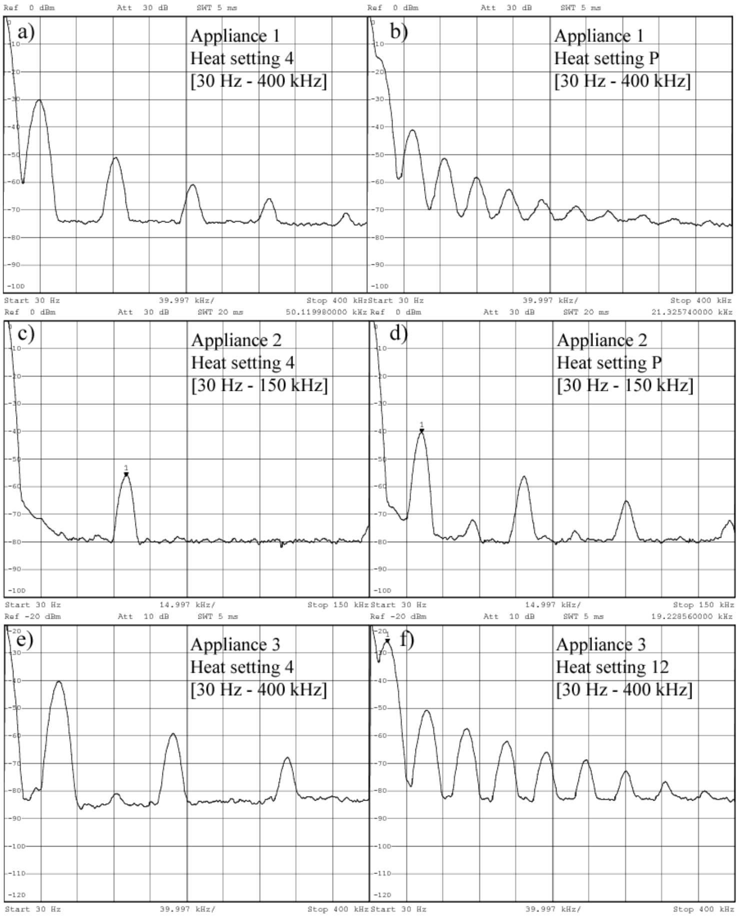


Figure 21: Harmonics contribution, in [dB] (power spectrum, 10 dB per division). Graphs a) and b), c) and d), e) and f) correspond to appliances 1, 2 and 3, with hobs 1, 2 and 1, respectively (largest hobs).

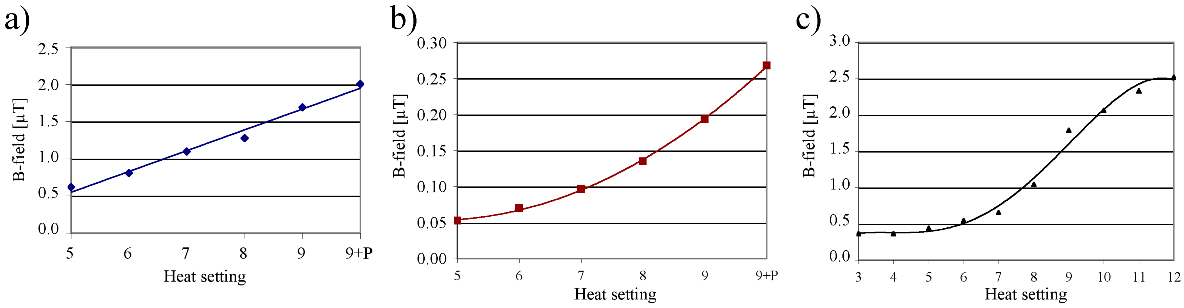


Figure 22: **Measured *B*-field exposure for different heat settings, for a) appliance 1, b) appliance 2 and c) appliance 3.** Measurements performed at the largest hob: hobs 1, 2 and 1 for appliances 1, 2 and 3, respectively, with pot 3 and lid, measuring distance of 5 cm and max. heating setting. Other measurement conditions according to EN50366.

4.3 Uncertainty Budget

Table 10 gives a list of probable sources of error and an evaluation of the uncertainty budget, as given in the IEEE 1528-2003 standard [9]. The uncertainty was assessed in the region of the test specification limit (6.25 μT) and for the full range of measurements. Moreover, during all experiments, the random components of uncertainty were reduced by performing repeated measurements (averaging $N = 4$, random components of uncertainty divided by $\sqrt{N} = 2$). The maximum uncertainty limits have been evaluated as follows [7, 8, 9]:

- **Narda probe ELT-400 measurement uncertainty.** The specification given by the manufacturer is ±4 % or ±0.34 dB for a signal in the frequency range 50 Hz to 120 kHz.
- **Error due to non-perfect frequency response of the probe.** The Narda probe ELT-400 frequency response deviation is less than ±0.80 dB or ±9.6 %.
- **Error due to non-perfect spherical isotropy of the probe.** As described in Chapter 4.1, the Narda probe ELT-400 spherical isotropy is very good, and the deviation is less than ±0.2 dB or ±2.3 %.
- **Error due to non-perfect linearity of the probe.** The deviation from linear response is $< \pm 0.05$ dB for B-fields exceeding 0.3 μT (see Chapter 4.1). The error increases for lower fields and equals 2.80 dB for B-fields of 0.06 μT. However, most of the B-fields measured exceeded 0.3 μT, and the uncertainty ±0.05 dB or ±0.6 % is considered.
- **Centering of the pot on the hob.** As discussed in Chapter 6.0.6, for pot displacements of ±4 mm (in every direction relative to the hob center) a maximum error of 11 % or ±0.90 dB is introduced.
- **Water volume and evaporation.** As shown in Chapter 6.0.7, the B-field variation due to changes in the volume of water in the pot is smaller than ±2.45 % or ±0.21 dB.
- **Probe alignment with respect to the appliance edge.** The probe alignment with respect to the appliance edge was verified before for each measurement with a worst-case accuracy of ±4 mm. It was calculated (Figures 24 to 29) that the corresponding B-field variations are smaller than ±2.2 % or ±0.19 dB when measuring in front of each hob.
- **Probe positioning on the DASY4 robot arm.** The mount made especially to fix the Narda probe ELT-400 on the robot arm has a notch which very precisely defines the probe position (±0.5 mm). This error was considered to be negligible.
- **Robot arm positioning.** The DASY4 robot arm positioning and repeatability is better than $\pm 1\,mm$. The corresponding measurement uncertainty was considered to be negligible.
- **Variation in the mains power supply.** The transfer function between the mains power supply and B-field variations was not assessed and assumed to be negligible.

Table 10: Measurement uncertainty evaluation. As described in IEEE 1528-2003, the tolerance, the probability distribution (R = Rectangular distribution), the divisor used to get standard uncertainty, the sensitivity coefficient c_i, the uncertainty components u_i and the combined standard uncertainty u_c are given.

Error Description	Tol. ($\pm dB$)	Prob. Dist.	Div.	c_i	u_i ($\pm dB$)	v_i
Narda probe ELT-400						
- Narda probe ELT-400 specification	±0.34	R	$\sqrt{3}$	1	±0.20	∞
- Error due to non-perfect frequency response	±0.80	R	$\sqrt{3}$	1	±0.46	∞
- Error due to non-perfect spherical isotropy	±0.20	R	$\sqrt{3}$	1	±0.12	∞
- Error due to non-perfect linearity	±0.05	R	$\sqrt{3}$	1	±0.03	∞
System repeatability						
- Centering of the pot on the hob	±0.90	R	$\sqrt{3}$	1	±0.52	∞
- Water volume and evaporation	±0.21	R	$\sqrt{3}$	1	±0.12	∞
- Alignment of probe to appliance edge	±0.19	R	$\sqrt{3}$	1	±0.11	∞
- Probe positioning on the robot arm	-					
- Robot arm positioning	-					
- Variation in the mains power supply	-					
Combined standard uncertainty u_c					**±0.75**	∞
Coverage factor for 95 %	**kp**= 2					
Expanded uncertainty					**±1.50**	

All error contributions considered are given in Table 10 and are assumed to be random and uncorrelated. In a conservative evaluation of all uncertainties, the error distribution is assumed to be rectangular. The combined uncertainty u_c is obtained by taking the square root of the sum of squares of the individual uncertainties u_i according to [7, 8, 9]:

$$u_c = \sqrt{\sum_{i=1}^{n} u_i^2} \tag{9}$$

Throughout this report all *B*-fields measured are given with the uncertainty $u_c = \pm 1.50\,\text{dB}$.

5 Assessments According to EN50366 conditions

One objective of this study was to measure whether the B-field exposure from the three selected induction cookers complies with the derived and basic restrictions of the ICNIRP guidelines, when assessed according to the European Norm EN50366.

5.0.1 Measuring Conditions in EN50366

The European Norm EN50366 describes a method for the evaluation and measurement of the electromagnetic field in the vicinity of appliances such as induction hobs and hotplates.

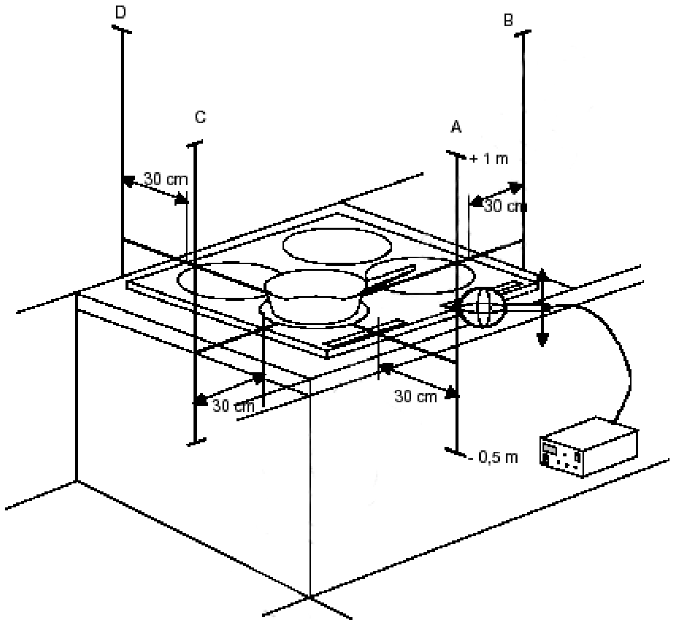


Figure 23: Measuring distances, according to EN50366. Lines (A, B, C, D) indicate the measuring positions for an induction cooker with 4 hobs in operation. The probe is here positioned on line A. [4]

Measuring distance and operator distance, according to EN50366 The *measuring distance* is the distance between the surface of the appliance and the closest point on the sensor surface. The *operator distance* is the distance between the surface of the appliance and the closest point of the head, limbs or torso of the operator. For each cooking zone, the measurements are made along four vertical lines (A, B, C, D) at a measuring distance of 30 cm from the edges of the appliance (see Figure 23). The measurements are made up to 1 m above the cooking zone and 0,5 m below it. The measurement is not made at the rear of the appliance if the appliance is intended to be used when placed against a wall.

Operating mode, according to EN50366 An enameled steel cooking vessel, filled to 50 % of its capacity with tap water, is placed centrally on the cooking zone to be measured. The smallest vessel recommended in the instructions for use is used. If no recommendations are provided, the smallest standard vessel that covers the marked cooking zone is used. The bottom diameters of standard cooking vessels are: 110 mm, 145 mm, 180 mm, 210 mm and 300 mm. The hobs are operated in turn at the highest power setting, with all other cooking zones uncovered. The measurements are made after stable operating conditions have been reached. If no stable conditions can be reached, an appropriate observation time (e.g., 30 s) shall be defined to be sure to get the maximum value with fluctuating field sources.

Implementation of EN50366 in this study The *B*-field exposure from the three appliances was assessed according to the operating mode given in EN50366, but with minimal adaptations. The measurements were made along vertical lines at a distance of 30 cm from the edges of the appliance (see Figure 23), but also at measuring distances of 1, 5 and 10 cm. The front, rear, left and right sides of the appliances (see Figure 6) were assessed: additional measurements were also made at the rear of the appliance, since modern kitchens often feature cooking islands which allow the cook to access the hobs from all sides. For these experiments, the standard set of pots was used (pots 3, 14a, 14b and 13, with bottom diameters of 22 cm, 18 cm, 18 cm and 14.5 cm, respectively, see Figure 9). The pots used were not made of enameled steel but of stainless steel, which is the most common vessel type available for induction cooking on the market. For each single-hob measurement the pot of corresponding size was filled to 50 % of its capacity with tap water and centered on the hob. Lids were placed on the pots to achieve more stable conditions during the measurements, and to prevent excessive evaporation in the laboratory. The measuring range along the z-axis was $[-0.4...0.4\,m]$ for appliances 1 and 2, and $[-0.7...0.3\,m]$ for appliance 3, due to the finite travel of the DASY4 robot arm. For Appliance 3, the measurements according to EN50366 were performed using pots 3 and 13 (largest and smallest pots of the standard set of pots, see Figure 9), since no vessel was recommended in the instructions and no cooking zone was marked on the appliance. The only relevant information given in the Inducs manual is to use a pot with a minimum diameter of 12 cm. The *B*-field measured for all three appliances was compared to the ICNIRP limit, which is $6.25\,\mu$T for general public exposure. The results are presented below.

5.0.2 Appliance 1

The *B*-field measured in the vicinity of appliance 1 is shown in Figures 24 (front and rear sides) and 25 (left and right sides). The *B*-field does not exceed the ICNIRP limit ($6.25\,\mu$T) for a measuring distance of 30 cm according to EN50366.

Figures 24 a) (hob 1, front side) and 24 g)(hob 3, rear side) show that the ICNIRP limit is exceeded for a measuring distance of 1 to 5 cm.

5.0.3 Appliance 2

Figures 26 (front and rear sides) and 27 (left and right sides) depict the *B*-field measured in the vicinity of appliance 2. The *B*-field does not exceed the ICNIRP limit ($6.25\,\mu$T) for a measuring distance of 30 cm according to EN50366.

Figures 27 c) (hob 3, left side), 27 e) (hob 1, right side) and 27 h)(hob 4, right side) show that the ICNIRP limit is exceeded for a measuring distance of 1 to 5 cm. In Figure 27 f)(hob 2, right side), the ICNIRP limit is exceeded for a measuring distance of 5 to 10 cm.

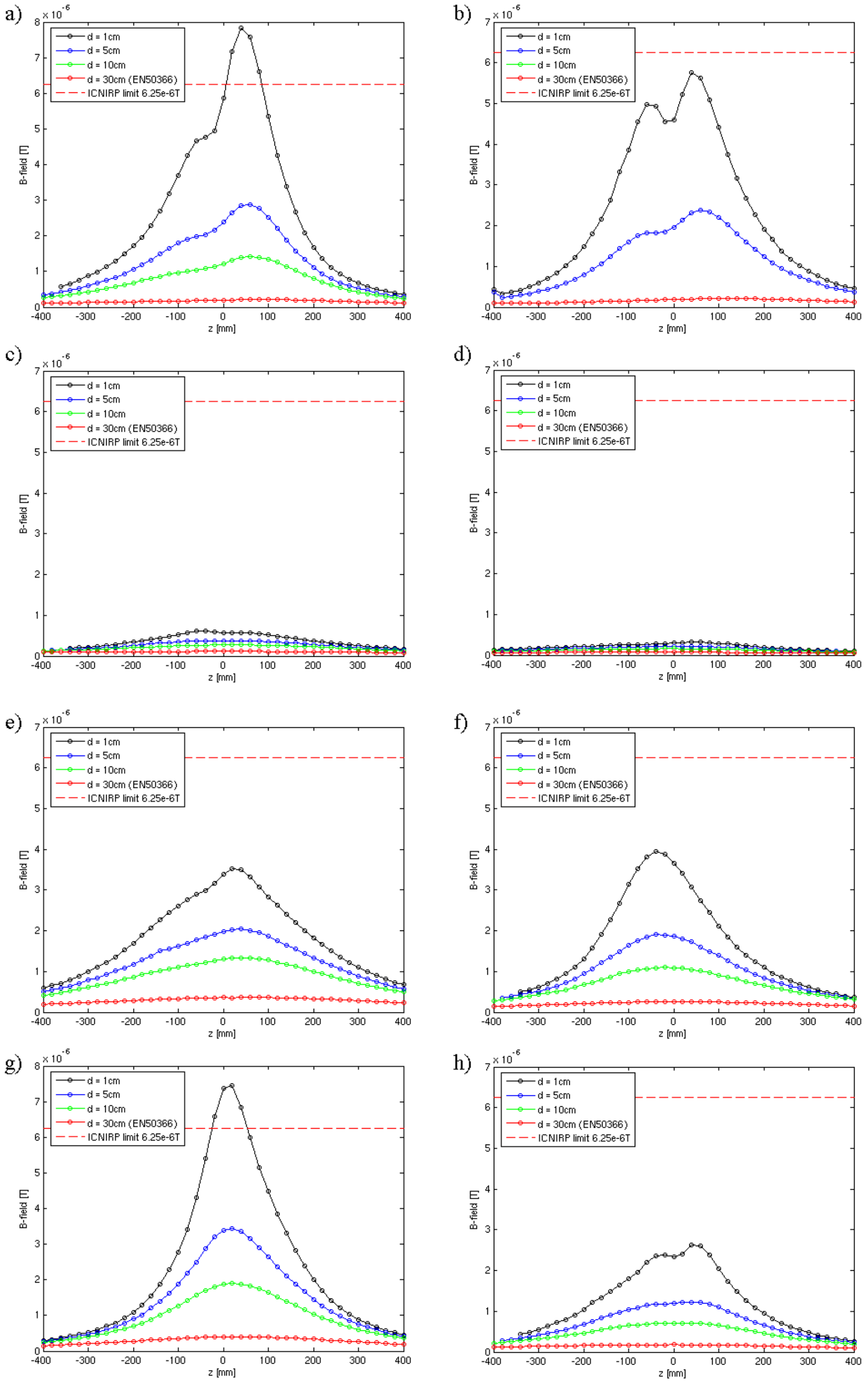


Figure 24: **Appliance 1, single-hob measurement using the standard set of pots (front and rear sides of the appliance).** Graphs a) to d) correspond to front side B-field measurements along the z-axis, in front of a) hob 1, b) hob 2, c) hob 3 and d) hob 4, at measuring distances of 1, 5, 10 and 30 cm. Graphs e) to h) correspond to rear side B-field measurements along the z-axis, in front of e) hob 1, f) hob 2, g) hob 3 and h) hob 4, at measuring distances of 1, 5, 10 and 30 cm. The other measuring conditions were according to EN50366. Hobs 1 to 4 were evaluated with single-hob measurements using the standard set of pots (pots 14a, 3, 14b and 13, centered on hobs 1, 2, 3 and 4, respectively).

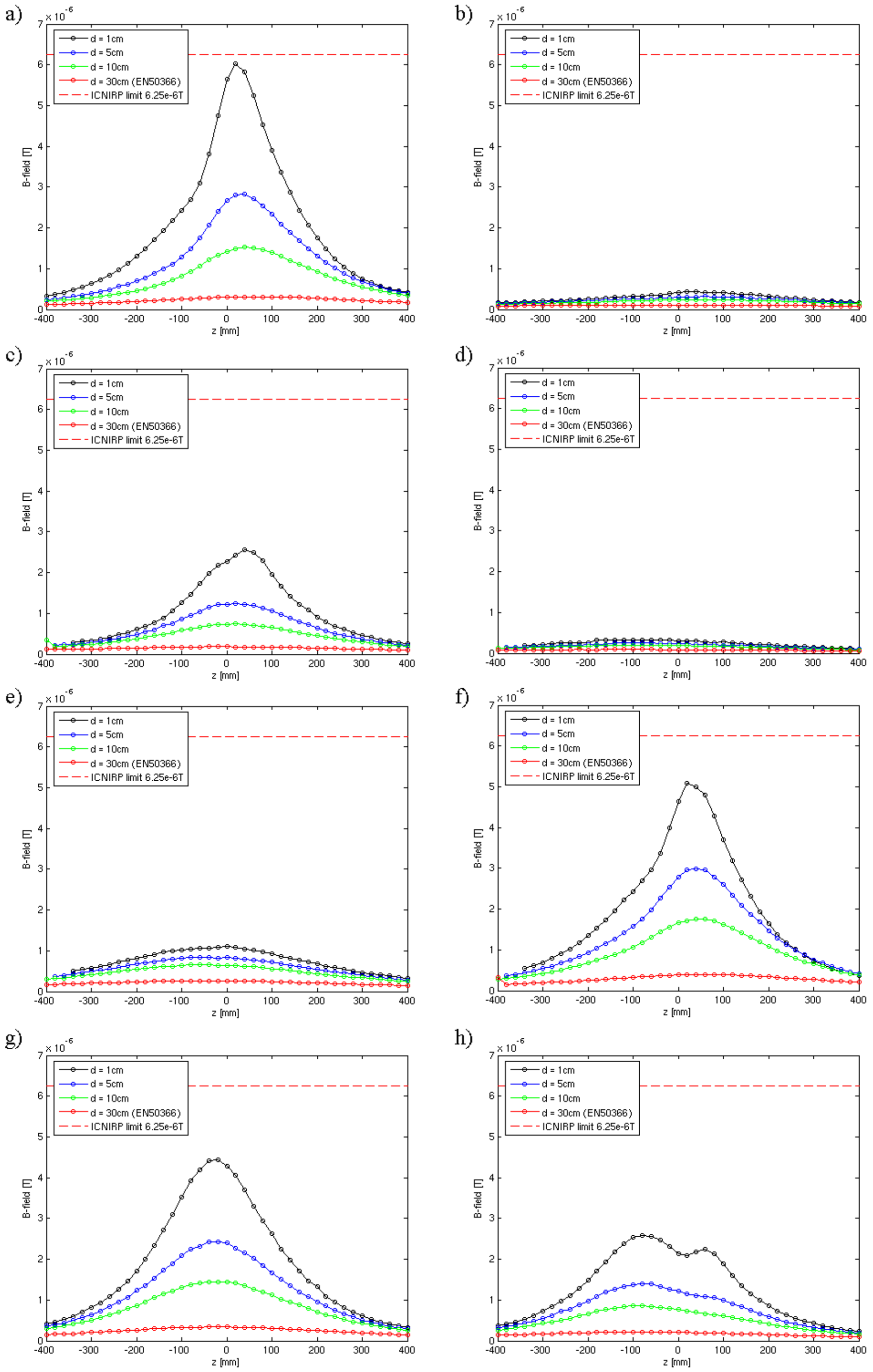


Figure 25: **Appliance 1, single-hob measurement using the standard set of pots (left and right sides of the appliance).** Graphs a) to d) correspond to left side B-field measurements along the z-axis, in front of a) hob 1, b) hob 2, c) hob 3 and d) hob 4, at measuring distances of 1, 5, 10 and 30 cm. Graphs e) to h) correspond to right side B-field measurements along the z-axis, in front of e) hob 1, f) hob 2, g) hob 3 and h) hob 4, at measuring distances of 1, 5, 10 and 30 cm. The other measuring conditions were according to EN50366. Hobs 1 to 4 were evaluated with single-hob measurements using the standard set of pots (pots 14a, 3, 14b and 13, centered on hobs 1, 2, 3 and 4, respectively).

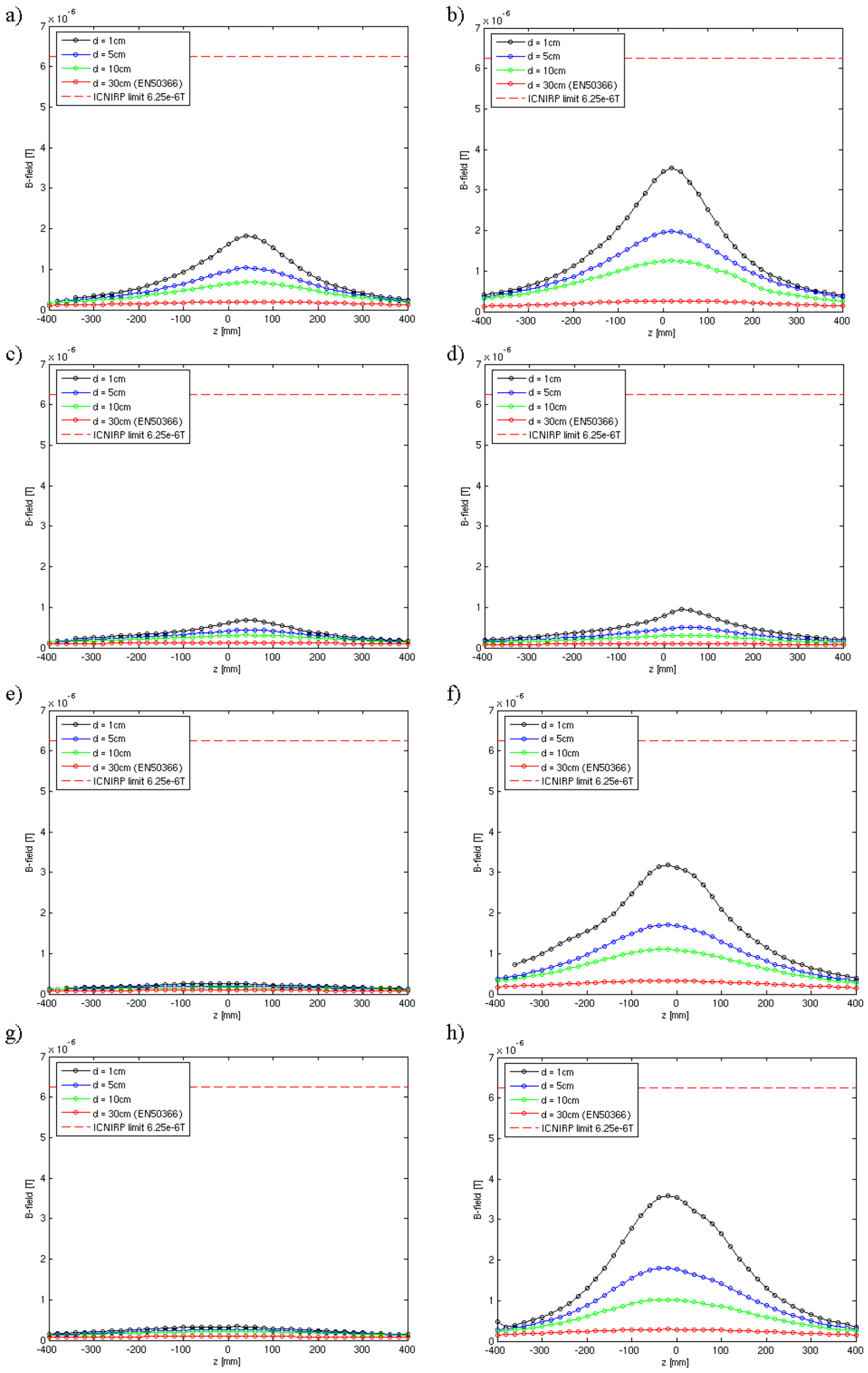


Figure 26: **Appliance 2, single-hob measurement using the standard set of pots (front and rear sides of the appliance).** Graphs a) to d) correspond to front side B-field measurements along the z-axis, in front of a) hob 1, b) hob 2, c) hob 3 and d) hob 4, at measuring distances of 1, 5, 10 and 30 cm. Graphs e) to h) correspond to rear side B-field measurements along the z-axis, in front of e) hob 1, f) hob 2, g) hob 3 and h) hob 4, at measuring distances of 1, 5, 10 and 30 cm. The other measuring conditions were according to EN50366. Hobs 1 to 4 were evaluated with single-hob measurements using the standard set of pots (pots 14a, 3, 14b and 13, centered on hobs 1, 2, 3 and 4, respectively).

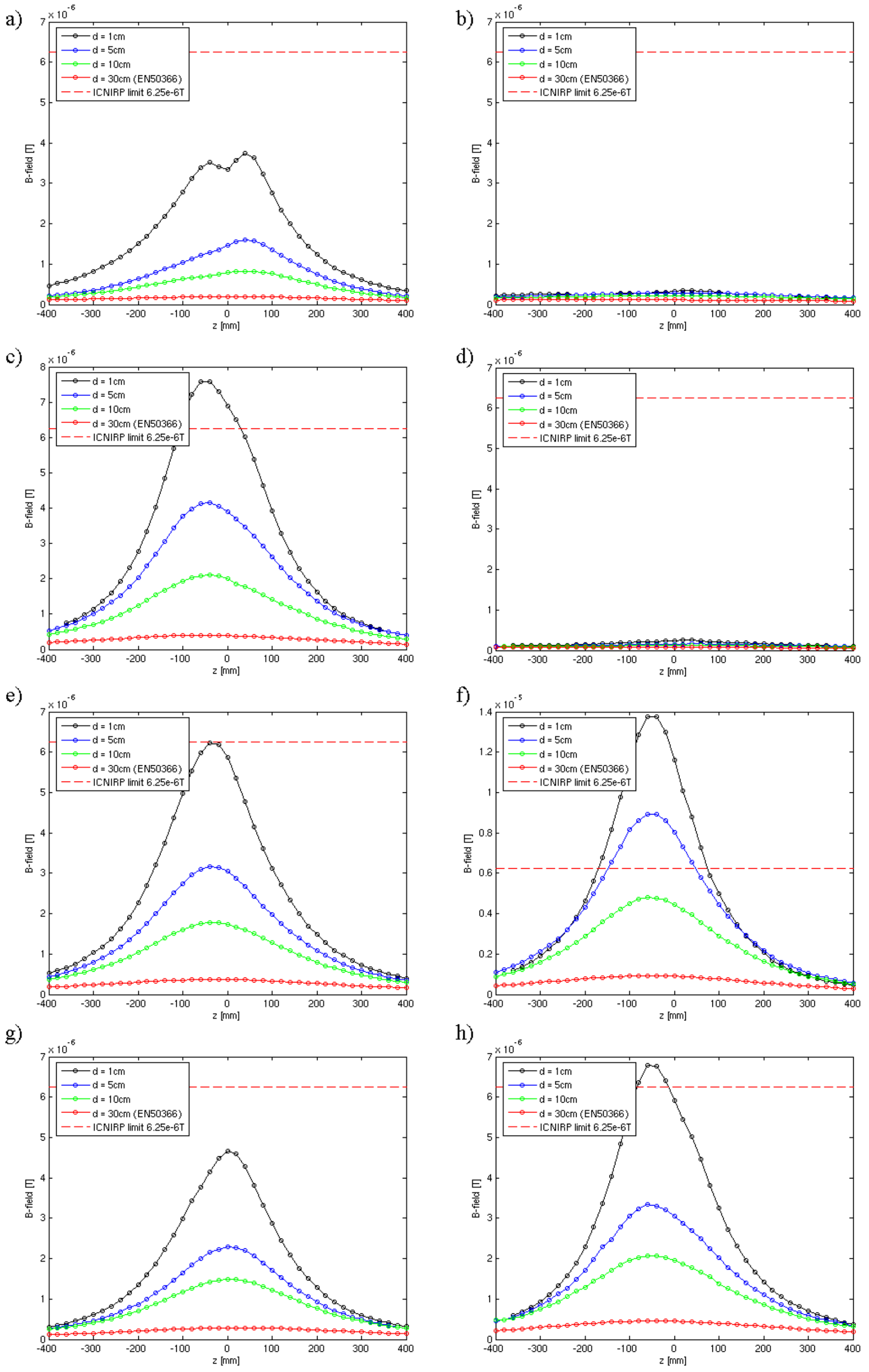


Figure 27: **Appliance 2, single-hob measurement using the standard set of pots (left and right sides of the appliance).** Graphs a) to d) correspond to left side B-field measurements along the z-axis, in front of a) hob 1, b) hob 2, c) hob 3 and d) hob 4, at measuring distances of 1, 5, 10 and 30 cm. Graphs e) to h) correspond to right side B-field measurements along the z-axis, in front of e) hob 1, f) hob 2, g) hob 3 and h) hob 4, at measuring distances of 1, 5, 10 and 30 cm. The other measuring conditions were according to EN50366. Hobs 1 to 4 were evaluated with single-hob measurements using the standard set of pots (pots 14a, 3, 14b and 13, centered on hobs 1, 2, 3 and 4, respectively).

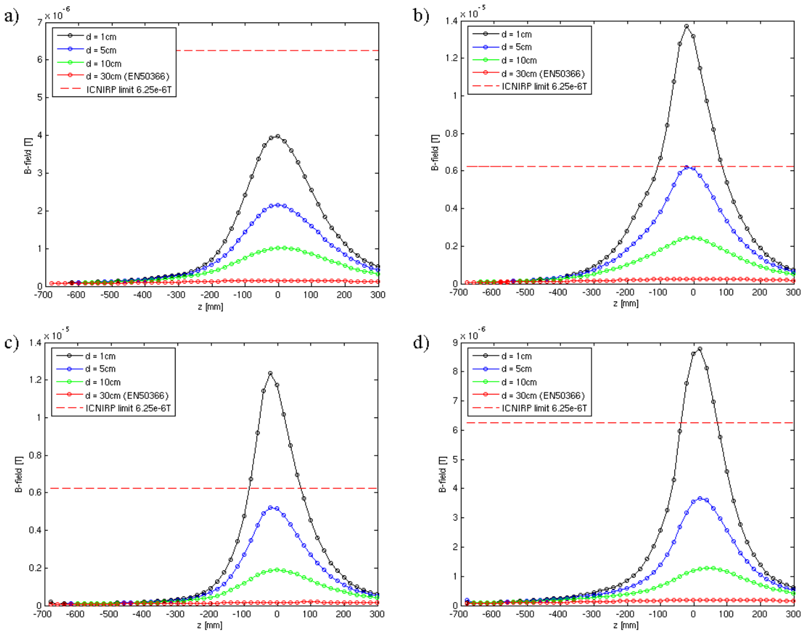


Figure 28: **Appliance 3, with pot 3 (large pot, standard set of pots).** The *B*-field is measured along the z-axis, on the a) front side, b) rear side, c) left side and d) right side of the appliance using pot 3 at measuring distances of 1, 5, 10 and 30 cm. The other measuring conditions were according to EN50366 with the pot centered on the hob.

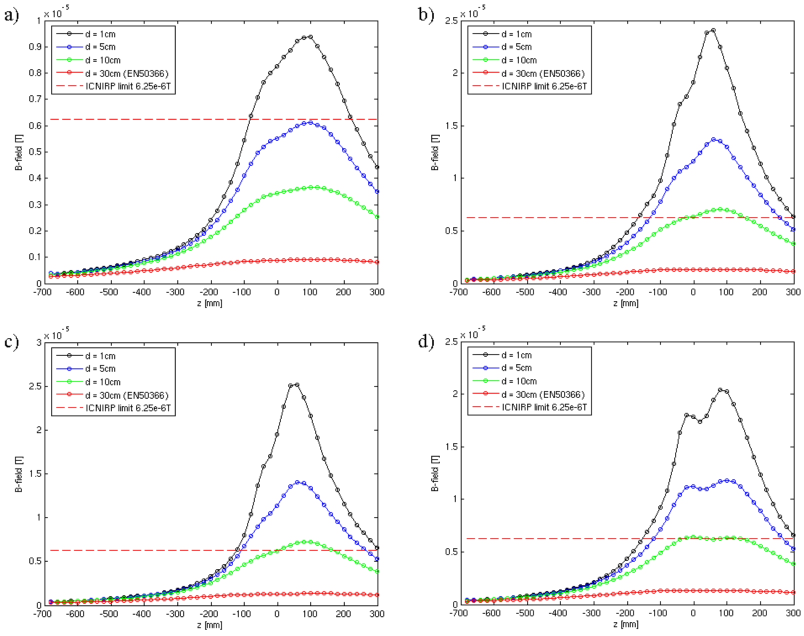


Figure 29: **Appliance 3, with pot 13 (small pot, standard set of pots).** The *B*-field is measured along the z-axis, on the a) front side, b) rear side, c) left side and d) right side of the appliance using pot 13 at measuring distances of 1, 5, 10 and 30 cm. The other measuring conditions were according to EN50366 with the pot centered on the hob.

5.0.4 Appliance 3

The B-field measured in the vicinity of appliance 3 is given in Figures 28 (large pot 3, standard set of pots) and 29 (small pot 13, standard set of pots). In both figures, the B-field is measured at the front, rear, left and right sides of the appliance. The B-field does not exceed the ICNIRP limit (6.25 μT) for a measuring distance of 30 cm according to EN50366.

However, for the large pot 3, Figure 28 c) (left side) and 28 d) (right side) show that the ICNIRP limit is exceeded for a measuring distance of 1 to 5 cm. In Figures 28 b) (rear side), the ICNIRP limit is exceeded for a measuring distance of 5 cm.

For the small pot 13, Figure 29 a) (front side) shows that the ICNIRP limit is exceeded for a measuring distance of 5 cm. In Figures 29 b), c) and d) (rear, left and right sides), the ICNIRP limit is exceeded for a measuring distance of 10 to 30 cm.

5.0.5 Discussion

For all three appliances, the B-field was measured following the recommendations given in EN50366, i.e., at a distance of 30 cm from the edge of the appliance using the standard set of pots. For appliances 1, 2 and 3, 6.5 % (-23.7 dB), 15 % (-16.5 dB) and 22 % (-13 dB) of the ICNIRP limit are reached at a measuring distance of 30 cm (see Table 11). Thus, the measured maximum B-field does not exceed the ICNIRP limit. However, for shorter distances corresponding to more realistic operator proximity, the B-field exceeds the ICNIRP guidelines.

Table 11: B-field measurement according to EN50366 at measuring distances of 30 and 1 cm, for appliances 1, 2 and 3 and for all hobs. The values measured at 30 cm are compared to the ICNIRP limit (6.25 μT).

Appliance	Hob	Measuring dist. [cm]	Front side meas. [μT]	Rear side meas. [μT]	Left side meas. [μT]	Right side meas. [μT]	Comparison with ICNIRP limit [dB]
1	1	1	7.9	3.6	6	1.1	
		30	0.21	0.36	0.31	0.27	-24.8
	2	1	5.8	4	0.44	5.2	
		30	0.21	0.26	0.10	0.39	-24
	3	1	0.6	7.5	2.6	4.5	
		30	0.11	0.41	0.18	0.34	-23.7
	4	1	0.32	2.7	0.36	2.6	
		30	0.07	0.18	0.09	0.22	-29
2	1	1	1.8	0.26	3.8	5.7	
		30	0.2	0.09	0.18	0.37	-24.6
	2	1	3.6	3.2	0.34	13.9	
		30	0.26	0.32	0.12	0.93	-16.5
	3	1	0.69	0.33	7.6	4.7	
		30	0.13	0.09	0.40	0.29	-23.9
	4	1	0.95	3.6	0.25	6.9	
		30	0.11	0.29	0.08	0.46	-22.7
3	1	1	4.0	13.4	12.0	9.0	
(pot 3)		30	0.16	0.26	0.19	0.20	-27.6
	1	1	9.7	24.7	26.3	21.1	
(pot 13)		30	0.93	1.4	1.4	1.4	-14

6 Worst-Case Exposure Conditions for Varied Loading of the Induction Cookers

The influence of several parameters was evaluated to assess the worst-case exposure.

6.0.6 Predominant Parameters

Pot-hob centering The predominant parameter is the centering of the pot on the hob. The B-field measured at a fixed position of the probe is minimal for perfect centering. However, the B-field increases by factors of approximately 3, 15 and 10 when the pan is displaced by 8 cm for appliances 1, 2 and 3, respectively (see Figure 30). For non-centering by ±4 mm in each direction, the B-field measured increases by approximately 2.5-4 %, 3-11 % and 5-10 % for appliances 1, 2 and 3, respectively.

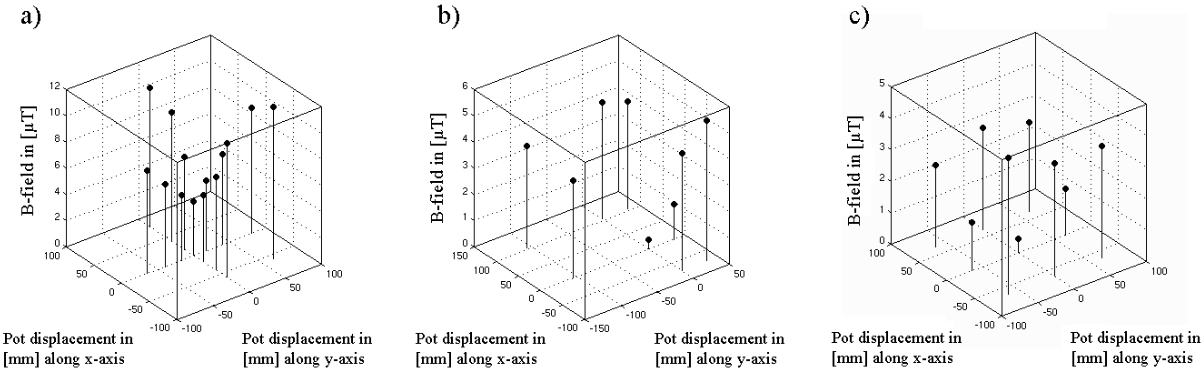


Figure 30: **Pot-hob centering, a) appliance 1, b) appliance 2 and c) appliance 3.** For each appliance, pot 3 (large pot, standard set of pots) was centered on the largest hob (hobs 1, 2 and 1 for appliances 1, 2 and 3, respectively). The Narda probe measured the B-field at a fixed position (front side of the appliance in front of the largest hob; measuring distance of 1 cm and heat setting 7 for appliances 1, 2 and 3). The pot was then displaced in the x and y directions, and the corresponding B-field was measured (the probe remained fixed). Other measuring conditions were according to EN50366.

Pot characteristics Other parameters leading to significant variation of the B-field include the bottom diameter, shape, bottom flatness and material grade (see Figure 31). Generally, the B-field measured increases with smaller bottom diameter, and it is larger when the pots are old or not perfectly flat.

Single-hob versus multi-hob use Simultaneous operation of several hobs is possible with appliances 1 and 2. This multi-hob use increases the total B-field exposure since the area of exposition is enlarged (see 6.1). However, in single-hob as well as in multi-hob use the B-field emitted by each hob is highly localized in the vicinity of the particular hob. Thus for multi-hob use the maximum B-field is still localized in front of the largest hob. Moreover, for multi-hob use it was found experimentally that the maximum B-field exposure does not necessarily correspond to all four hobs switched on simultaneously. The maximum B-field exposure corresponding to

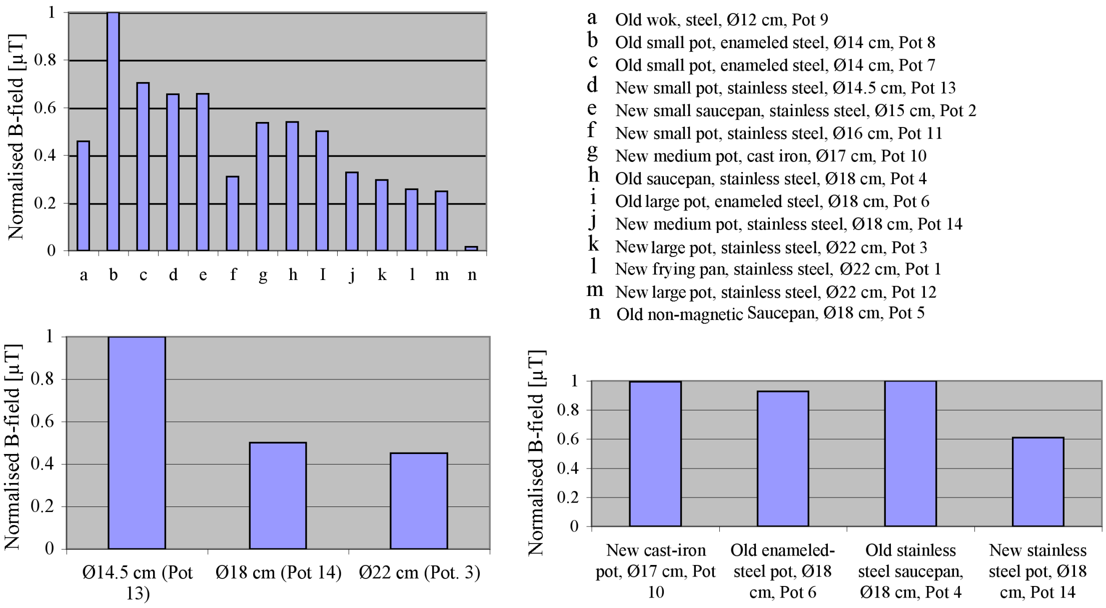


Figure 31: **Influence of pot characteristics (bottom diameter, shape, bottom flatness and material grade) on the B-field measured.** a) Normalized B-field measured for each pot (pots ranked from smallest to largest bottom diameter). b) Standard set of pots; the measured B-field decreases when the bottom diameter increases. c) For four pots with the same bottom diameter, the B-field measured depends on the pot characteristics (material, flatness). Measurements using appliance 3; the pots are centered and filled to 50 % of their capacity with tap water; lids used when available.

the worst-case scenario depends strongly on the pot, hob and appliance combination (see Chapter 6.1.1).

6.0.7 Negligible Parameters

The following parameters have also been evaluated and can be neglected since their contribution amounts to less than 5 % of the B-field variations. These include the volume of water in the pot, content of the pot (e.g., tap water, salt-water, vegetable oil), lid on pot, handle position, proximity to a magnet or paramagnetic object (cooking utensil).

Volume of water in the pot Stable operation conditions are reached when the water boils, i.e., after approximately 4 to 6 minutes (H_2O phase transition). While the water is boiling, the B-field is almost constant (see Figure 32) and the field variations remain less than ±2.45 % for appliances 1, 2 and 3. Figure 32 shows that for all three appliances, the B-field measured does not significantly depend on the duration of the measurement (the power supplied by the appliance is stable over time). Moreover, the B-field measured does not depend on the volume of water in the vessel, except when there is almost no water remaining in the pot (in that case the pot quickly becomes very hot and the B-field increases rapidly before the appliance automatically stops).

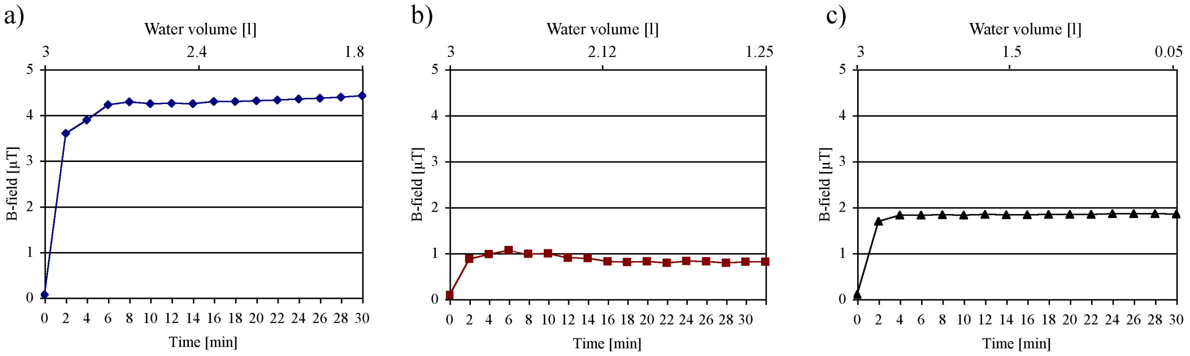


Figure 32: **Influence of the volume of water and the duration of measurements on the B-field measured, a) appliance 1, b) appliance 2, and c) appliance 3.** For each appliance, pot 3 (large pot, standard set of pots) is centered on the largest hob (hobs 1, 2 and 1 for appliances 1, 2 and 3, respectively). The pot is initially filled with 3 l of tap water. Measuring distance of 1 cm, heat setting 8. The B-field is measured over a period of 30 minutes, and the water evaporation is reduced using a lid.

Pot content Figure 33 compares the B-field measured using salt-water (see Figure 33 a) and vegetable oil (see Figure 33 b) compared with tap water. In both cases, the corresponding B-field variations are less than ±1 % ($\Delta B/B_{average} = \pm 0.55\,\%$ and $\Delta B/B_{average} = \pm 0.85\,\%$, respectively).

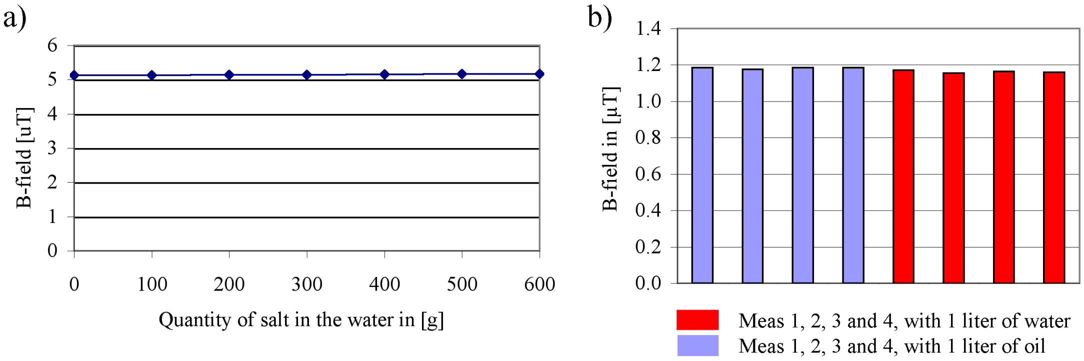


Figure 33: **Influence of pot content (salt-water, vegetable oil and tap water) on the B-field measured.** a) Salt-water. Measurement of the B-field with salt added to tap water (1 l of tap water at 25°C reaches saturation with approximately 400 g of salt). Appliance 1, pot 3 without lid initially filled with 1 l of tap water, hob 1, measuring distance 1 cm, heat setting 8. b) Comparison between tap water and vegetable oil. Appliance 3, pots 11a and 11b filled with 1 l of tap water and 1 l of vegetable oil, respectively, without lid, measuring distance 1 cm, heat setting 8.

Lid on pot The B-field measured slightly increases when using a lid on the pot; however this variation is less than 3 %. Nevertheless, the rate of evaporation is reduced by approximately a factor of 4 when using a lid, allowing longer measurement times, while maintaining constant measuring conditions. A lid was used for all of the DASY4 robot measurements.

Handle position In the case of frying-pan and saucepans, the handle position has a noticeable influence on the B-field exposure. However, no general rule could be established, and the variation of the B-field depends strongly on the pot, hob and appliance combination. For that reason, the most appropriate handle position was chosen: For single-hob measurement, the handle was aligned on the right side (y-direction), and for multi-hob measurement, the handle was aligned on the right for hobs 1 and 3, and on the left sides for hobs 2 and 4 (y-direction).

Proximity to a magnet and paramagnetic object (cooking utensil) The manufacturer recommends not to place cooking utensils, aluminum foil or magnets on the hob when it is switched on (risk of burning). Measurements of the B-field variation were performed, and it appears that depending on the object (e.g., magnet and paramagnetic utensil) and depending on the location (between the appliance and the probe, on the side of the hob), the B-field variation is $-5\,\% < \Delta B/B_{average} < 1.5\,\%$.

6.1 Induction Cookers B-Field Assessment

The second objective of this study was to evaluate the worst-case exposure for realistic use of the three selected induction cooking devices, and to assess whether compliance is maintained with the ICNIRP guideline ($6.25\,\mu$T for general public exposure).

6.1.1 Definition of Several Scenarios Corresponding to Standard and Worst-Case Exposures

In Chapter 6, the influence of several parameters was evaluated to assess the worst-case exposure. The predominant parameters (see Chapter 6.0.6) were used to define the exposure scenarios, combining single- and multi-hob use, pans centered and not, and the standard or worst-case set of pans (see 3.3).

Standard exposure scenarios The standard set of pots (see Chapter 3.3.1) was used in the scenarios summarized in Table 12. 14 standard scenarios were selected, combining single- and multi-hob use, and pan centered and not. For Appliance 3, the single-hob standard measurements were performed using pots 3 and 13 (largest and smallest pots of the standard set of pots, see explanation in Chapter 5.0.1).

Figure 34 shows the pot locations for non-centered measurements. In order to measure the worst-case exposure on each side for multi-hob measurements with appliance 1, the heat settings (P, P) were selected for hob pairs $(1, 2)$, $(3, 4)$, $(1, 3)$ and $(2, 4)$ for front, rear, left and right side measurements, respectively. Similarly, for non-centered pots on appliance 3, the pot location was chosen to differ for the front, rear, left and right side measurements (see Figures 34 c) and 34 f)). Appliance 3 is portable. The cook can choose to place it according to his needs and available space, and thus it may be accessed from the rear, left and right sides. For this reason, the B-field exposure of appliance 3 was assessed from all sides.

Worst-case exposure scenarios The worst-case set of pots (see 3.3.2) was used in the scenarios given in Table 13. A total of 12 scenarios were selected, combining single- and multi-

Table 12: Standard scenarios (using the standard set of pots) defined to measure the B-field emitted by the 3 induction cookers using the DASY4 robot system.

	Appliance	Hob(s)	Pot(s)	Heat setting	App. sides	Centered
Single-hob measurement	1	1 to 4	3, 14a, 14b, 13	P	4	yes/no
	2	1 to 4	3, 14a, 14b, 13	P	4	yes/no
	3	1	3	12	4	yes/no
	3	1	13	12	4	yes/no
Multi-hob measurement	1	1	3	P	4	yes/no
		2	14a	P		
		3	14b	8		
		4	13	7		
	1	1	3	P	4	yes/no
		3	14a	P		
	2	1	14a	9	4	yes/no
		2	3	9		
		3	14b	9		
		4	13	9		

Table 13: Worst-case scenarios (using the worst-case set of pots), defined to measure the B-field emitted by the 3 induction cookers using the DASY4 robot system.

	Appliance	Hob(s)	Pot(s)	Heat setting	App. sides	Centered
Single-hob measurement	1	1	8	P	4	yes/no
	2	2	8	P	4	yes/no
	3	1	8	12	4	yes/no
Multi-hob measurement	1	1	8	P	4	yes/no
		2	13	P		
		3	2	8		
	1	1	8	P	4	yes/no
		2	13	P		
	2	1	7	9	4	yes/no
		2	8	P		
		3	2	9		

hob use, and pan centered and not. The worst-case exposure depends on the combinations of pot/hob/appliance. The pots for the worst-case scenarios where chosen experimentally.

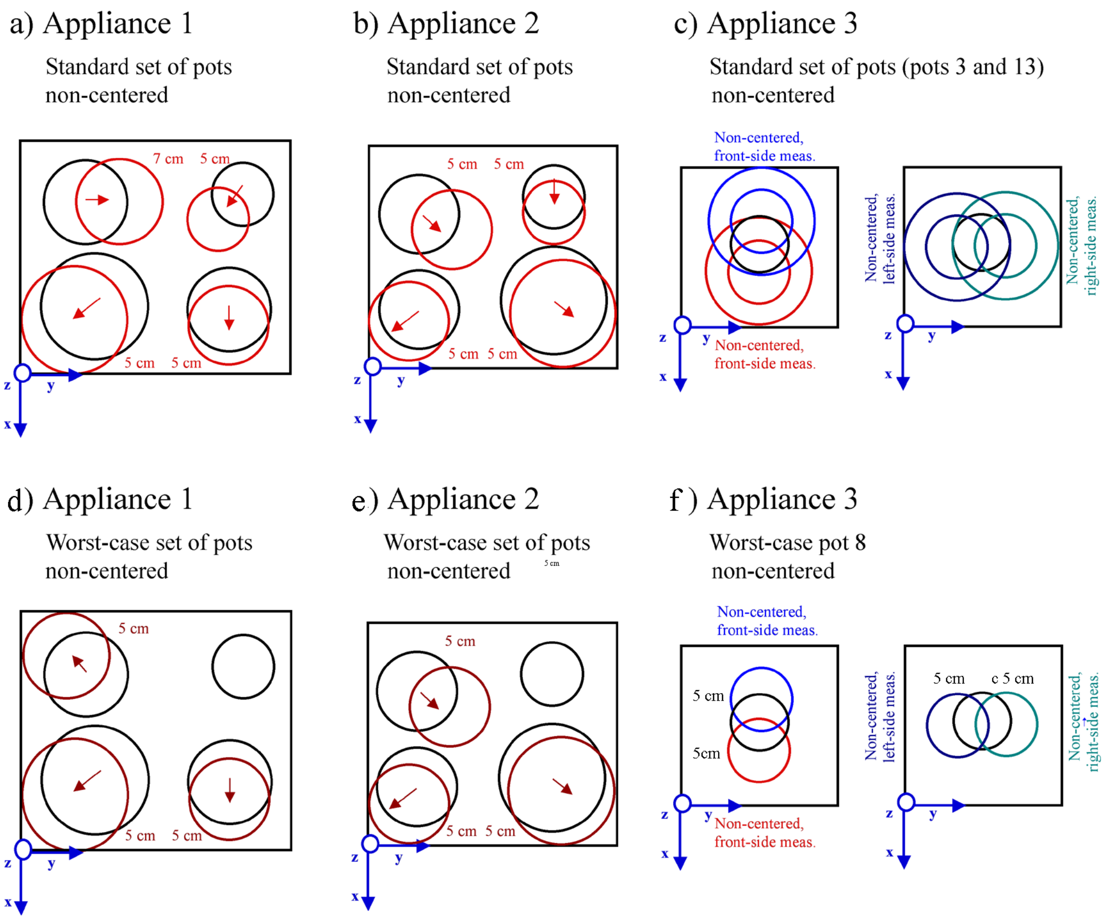


Figure 34: **Localization of the pots during standard and worst-case, single- and multi-hob measurements:** a) and d) appliance 1, b) and e) appliance 2, c) and f) appliance 3.

6.1.2 Appliance 1

Single-hob measurement using the standard set of pots Figure 35 shows the *B*-field measured in the vicinity of appliance 1, with only hob 1 switched on and using standard pot 3 centered and non-centered. The *B*-field does not exceed the ICNIRP limit ($6.25\,\mu$T) for a measuring distance of 30 cm, according to EN50366.

Figures 35 a) to e), f), g) and h) show that the ICNIRP limit is exceeded for measuring distances of 2, 3, 1 and 3 cm for the front, rear, left and right sides of the appliance, respectively. Figures 35 i) and j) show the *B*-field for pot 3 centered and not (front side of the appliance, see Figure 34 a)). The ICNIRP limit is exceeded for measuring distances of 2.2 cm and 5.5 cm when the pot is centered and non-centered, respectively. The maximum *B*-field values at a measuring distance of 1 cm are $7.2\,\mu$T (pot centered) and $13\,\mu$T (pot non-centered).

Multi-hob measurement using the standard set of pots Figure 36 shows the B-field measured in the vicinity of appliance 1, with hobs 1, 2, 3 and 4 switched on simultaneously (multi-hob measurement) and using the standard set of pots centered and non-centered. The B-field does not exceed the ICNIRP limit (6.25 μT) for a measuring distance of 30 cm, according to EN50366.

Figures 36 a), e) and f) show that the ICNIRP limit is exceeded for measuring distances of 1 to 5 cm and 5 to 10 cm when the pots are centered and non-centered, respectively. The corresponding maximum rms-values of the measured B-field are 8.6 μT and 13 μT (measuring distance of 1 cm).

Figure 37 depicts the B-field measured in the vicinity of appliance 1, with hobs 1 and 2 switched on simultaneously (multi-hob measurement) and using the standard set of pots centered. The maximum rms-value of the B-field when only two hobs are switched on is 8.5 μT (measuring distance of 1 cm), which is almost equal to the B-field measured when all four hobs are switched on.

Single-hob measurement using pot 8, worst-case set of pots Figure 38 shows the B-field measured in the vicinity of appliance 1, with only hob 1 switched on and using pot 8 (worst-case set of pots) centered and non-centered. The B-field does not exceed the ICNIRP limit (6.25 μT) for a measuring distance of 30 cm, according to EN50366.

Figures 38 a), b) and e) (pot centered) and 38 f), g), h) and j) (pot non-centered) show that the ICNIRP limit is exceeded for measuring distances of 9 cm and 15 cm when the pots are centered and non-centered, respectively. The corresponding maximum rms-values of the B-field measured are 21 μT and 38 μT (measuring distance of 1 cm).

Multi-hob measurement using the worst-case set of pots Figure 39 illustrates the B-field measured in the vicinity of appliance 1, with hobs 1, 2 and 3 switched on simultaneously (multi-hob measurement employing three hobs) and using the worst-case set of pots (pots 8, 13 and 2 on hobs 1, 2 and 3, respectively) centered and non-centered. The B-field does not exceed the ICNIRP limit (6.25 μT) for a measuring distance of 30 cm, according to EN50366.

Figures 39 a), b) and e) (pot centered) and 39 f), g), h) and j) (pot non-centered) show that the ICNIRP limit is exceeded for measuring distances of 9 cm and 15 cm when the pots are centered and non-centered, respectively. The corresponding maximum rms-values of the B-field measured are 21 μT and 36 μT (measuring distance of 1 cm).

The same results are found in Figure 40, when two hobs instead of three are switched on simultaneously. The values are the same for one, two or three hobs switched on simultaneously when using the worst-case set of pots. However, the B-field exposure area is larger with multi-hob than with single-hob measurement.

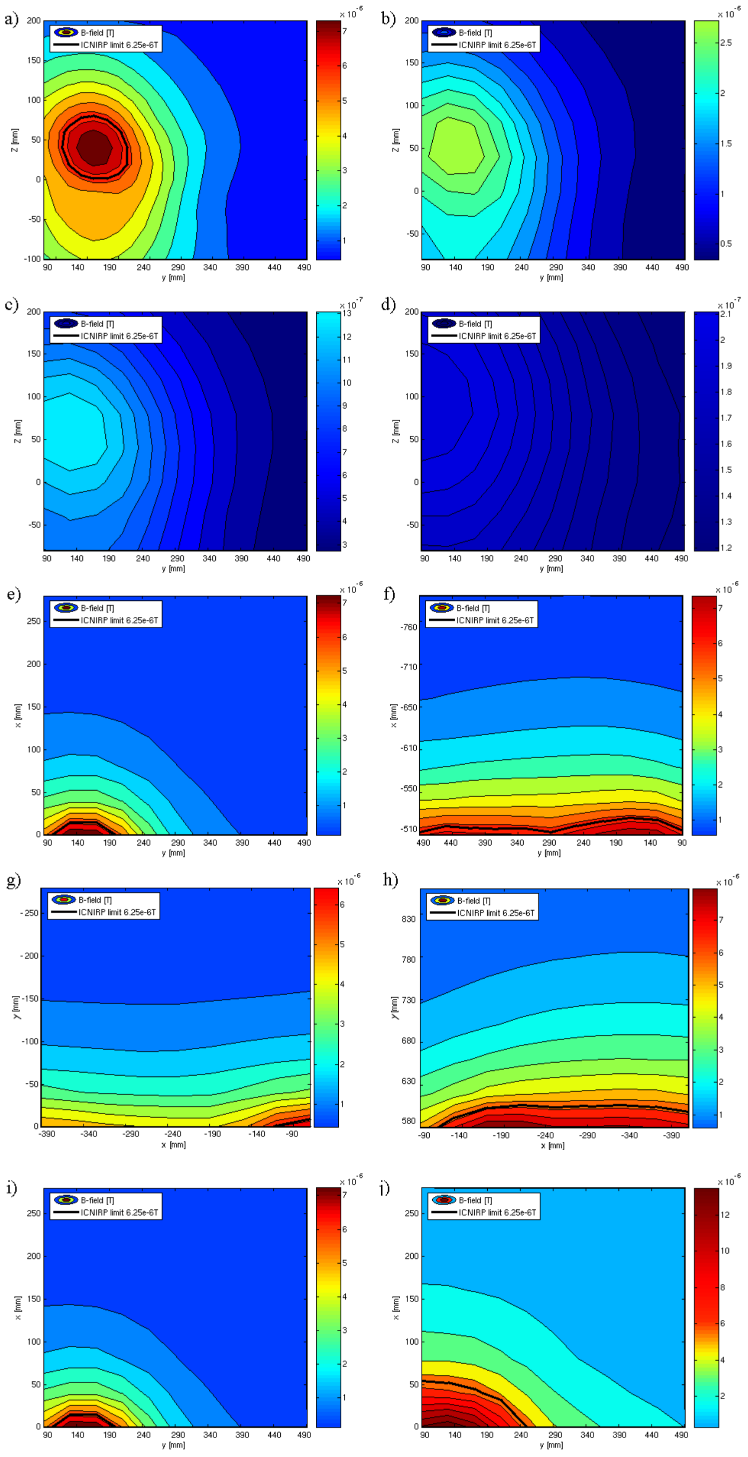


Figure 35: **Appliance 1 single-hob measurement using the standard set of pots:** In Graphs a) to d), the B-field is measured in the vertical plane (y, z) at the front side of the appliance, at measuring distances of a) 1 cm, b) 5 cm, c) 10 cm and d) 30 cm. In Graphs e) to h), the B-field is measured in the horizontal plane. Graphs e), f), g) and h) correspond to the front, rear, left and right sides of the appliance, respectively. Graphs i) and j) show a comparison between i) pot centered, and j) pot non-centered; the B-field is measured in the horizontal plane, at the front side of the appliance. Hob 1 is switched on (single-hob measurement), using the standard pot 3 centered; other measuring conditions according to EN50366.

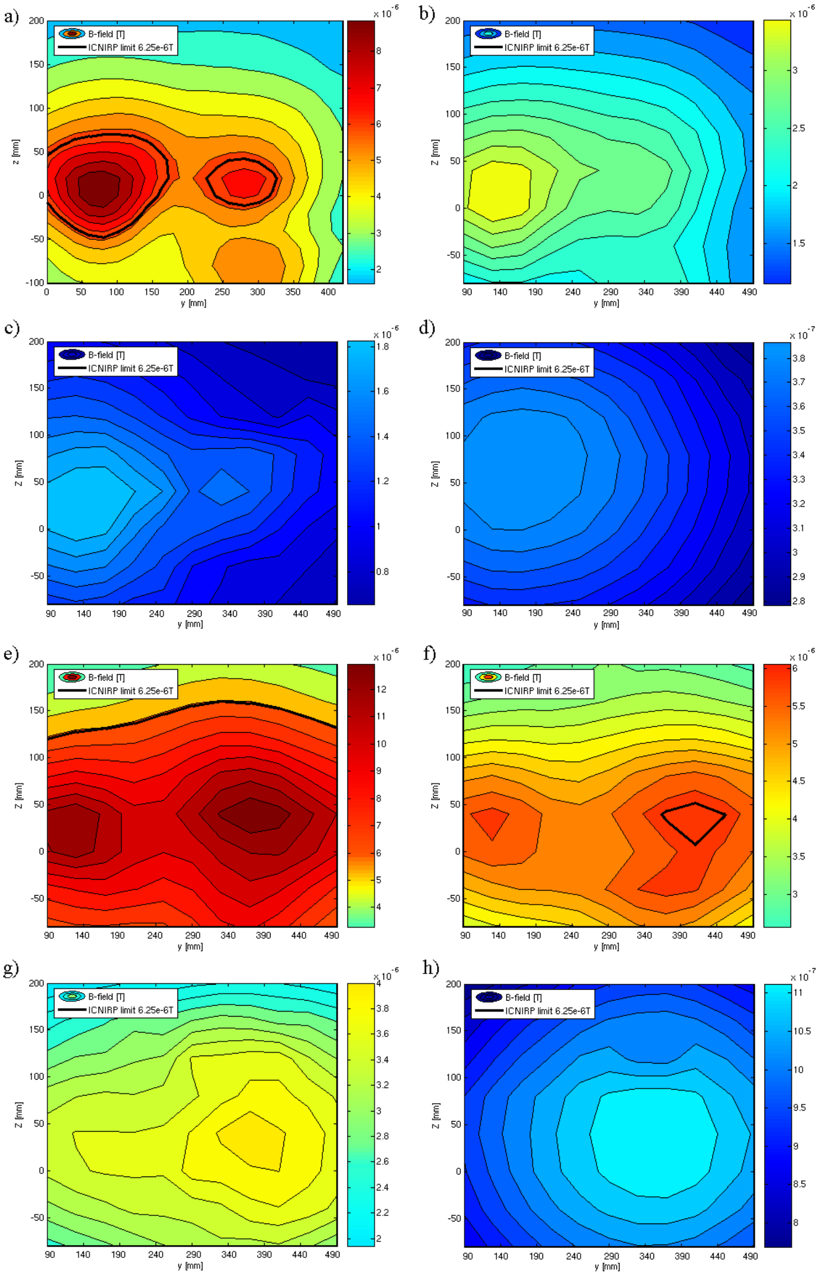


Figure 36: **Appliance 1 multi-hob measurement (four hobs) using the standard set of pots. Comparison of the B-field when the pots are a) to d) centered, and e) to h) non-centered (front side of the appliance):** The B-field is measured in the vertical plane (y, z), at measuring distances of a) 1 cm, b) 5 cm, c) 10 cm and d) 30 cm. Hobs 1, 2, 3 and 4 are switched on simultaneously (multi-hob measurement), using the standard set of pots (pots 3, 14a, 14b and 13 on hobs 1, 2, 3 and 4, respectively); other measuring conditions according to EN50366.

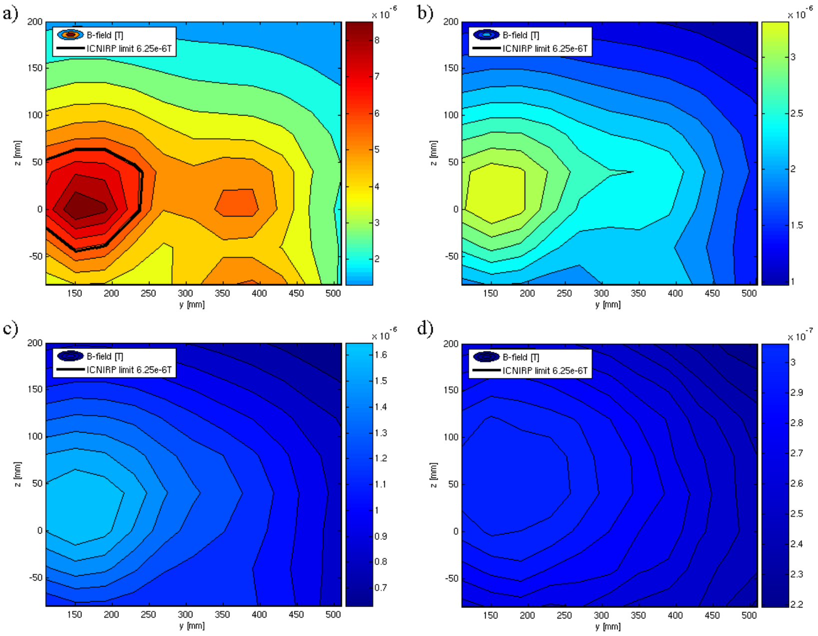


Figure 37: **Appliance 1 multi-hob measurement (two hobs) using the standard set of pots (front side of the appliance):** The B-field is measured in the vertical plane (y, z), at measuring distances of a) 1 cm, b) 5 cm, c) 10 cm and d) 30 cm. Hobs 1 and 3 are switched on simultaneously (multi-hob measurement), using the standard set of pots (pots 3 and 14a on hobs 1 and 3, respectively), other measuring conditions according to EN50366. The pots are centered.

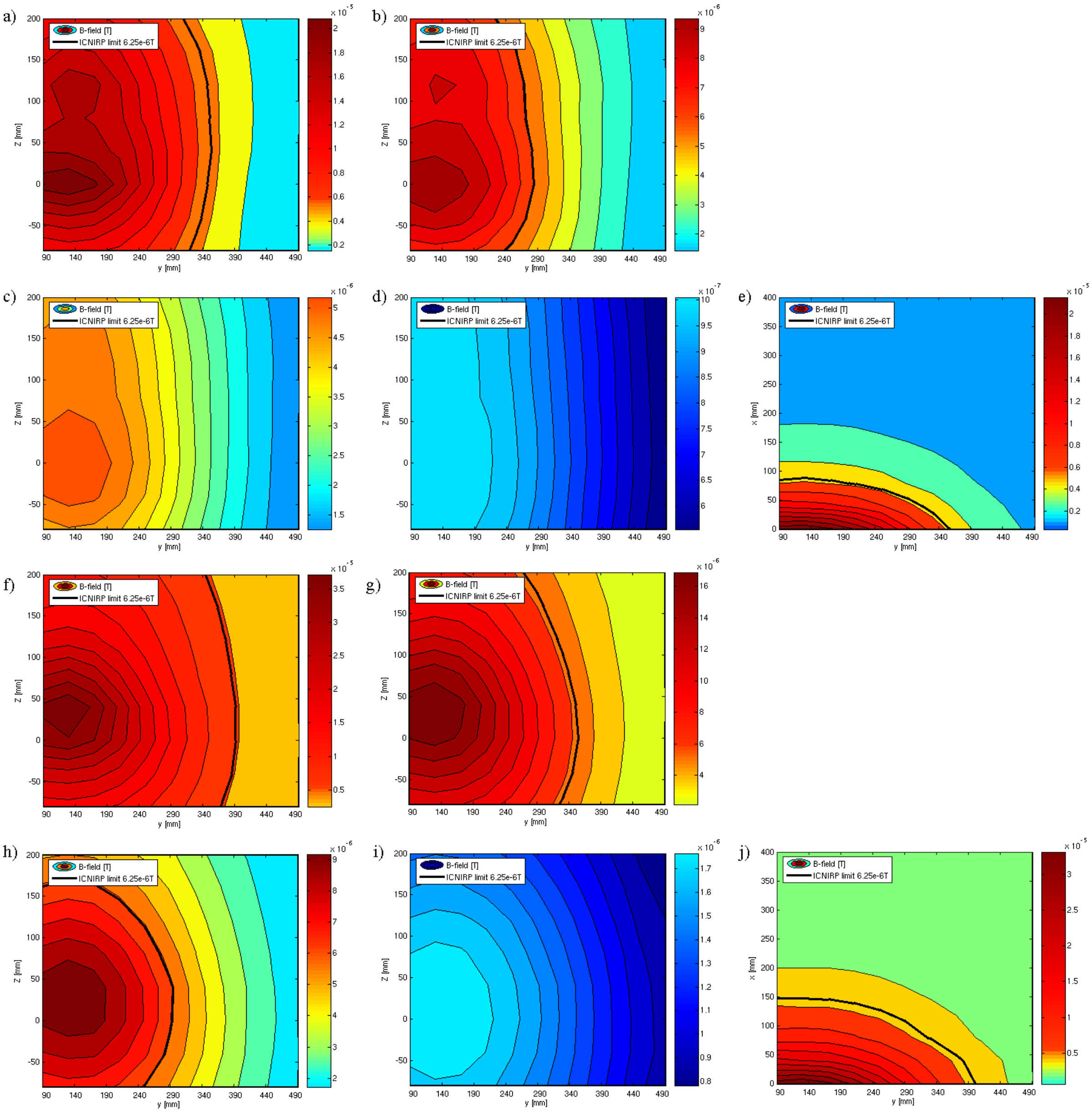


Figure 38: **Appliance 1 single-hob measurement using the worst-case set of pots (front side of the appliance). Comparison of the *B*-field when the pot is a) to e) centered, and f) to j) non-centered:** In Graphs a), b), c), d), f), g), h) and i), the *B*-field is measured in the vertical plane (y, z) at measuring distances of 1, 5, 10, 30, 1, 5, 10 and 30 cm, respectively. In Graphs e) and j), the *B*-field is measured in the horizontal plane. Hob 1 is switched on (single-hob measurement), and pot 8 (worst-case set of pots) is used.

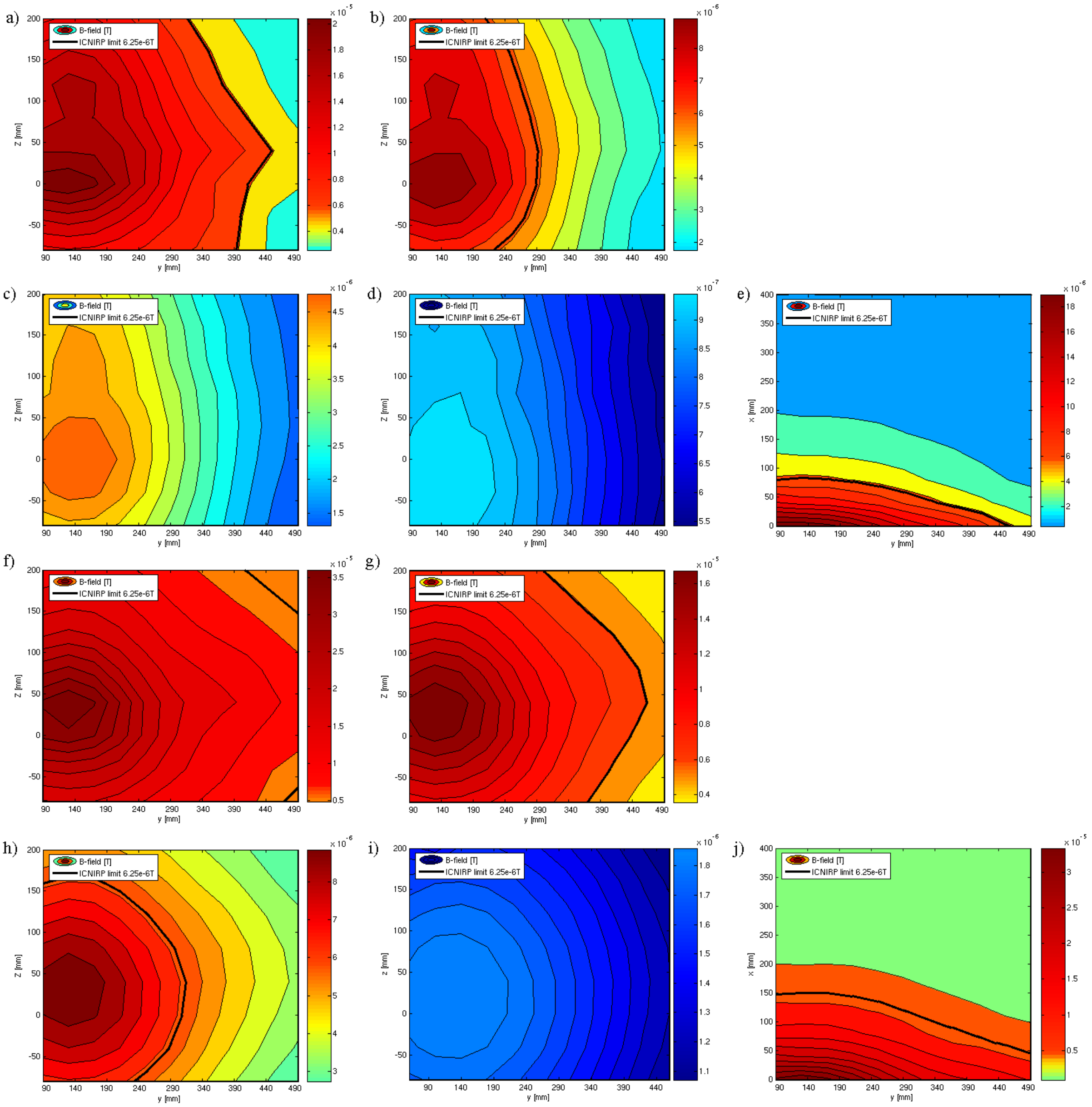


Figure 39: **Appliance 1 multi-hob measurement (three hobs) using the worst-case set of pots (front side of the appliance). Comparison of the *B*-field when the pot is a) to e) centered, and f) to j) non-centered:** In Graphs a), b), c), d), f), g), h) and i), the *B*-field is measured in the vertical plane (y, z), at measuring distances of 1, 5, 10, 30, 1, 5, 10 and 30 cm, respectively. In Graphs e) and j), the *B*-field is measured in the horizontal plane. Hobs 1, 2 and 3 are switched on simultaneously (multi-hob measurement), using the worst-case set of pots (pots 8, 13 and 2 for hobs 1, 2 and 3, respectively).

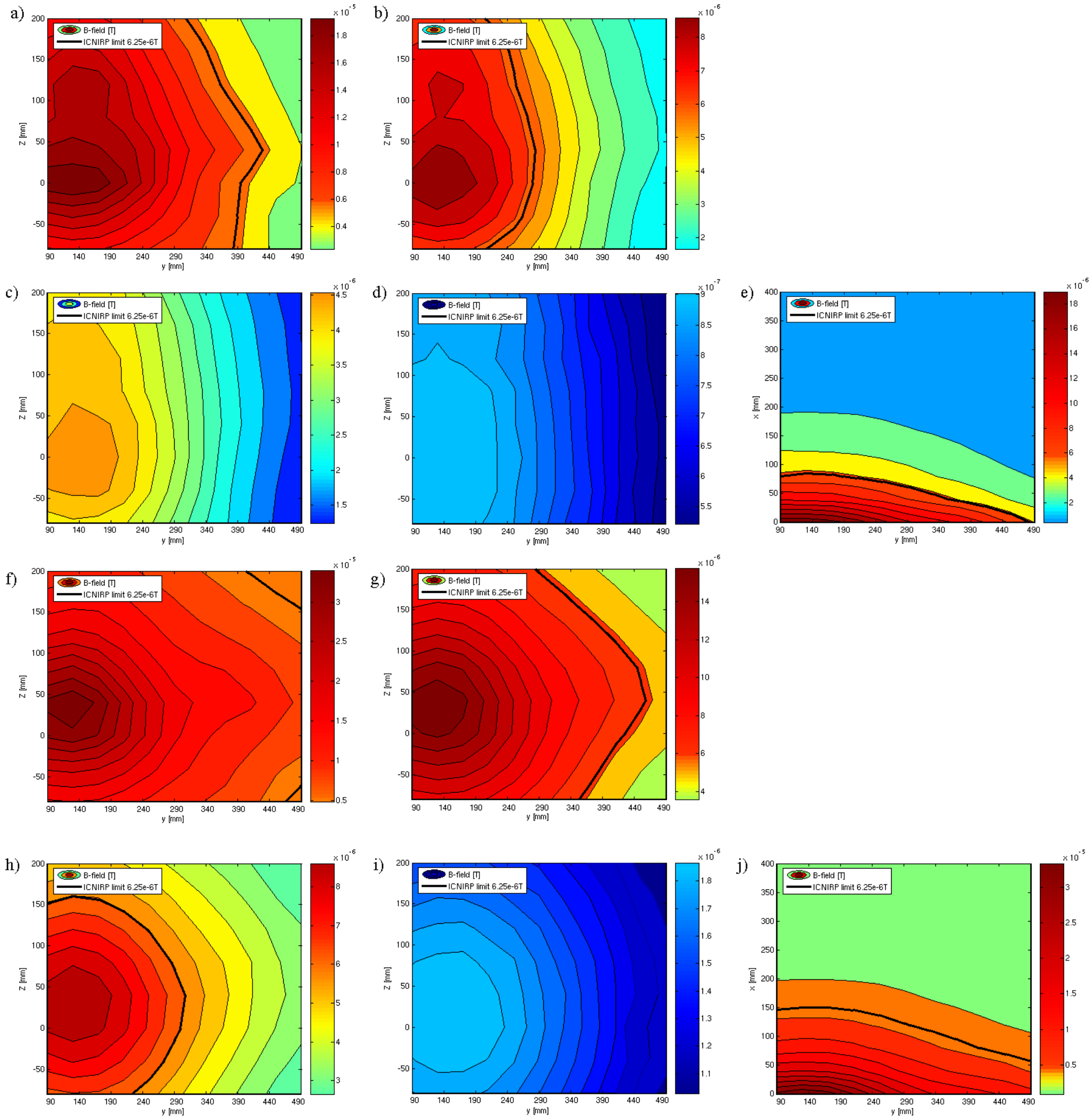


Figure 40: **Appliance 1 multi-hob measurement (two hobs) using the worst-case set of pots (front side of the appliance). Comparison of the B-field when the pot is a) to e) centered, and f) to j) non-centered:** In Graphs a), b), c), d), f), g), h) and i), the B-field is measured in the vertical plane (y, z), at measuring distances of 1, 5, 10, 30, 1, 5, 10 and 30 cm, respectively. In Graphs e) and j), the B-field is measured in the horizontal plane. Hobs 1 and 2 are switched on simultaneously (multi-hob measurement), using the worst-case set of pots (pots 8, and 13 for hobs 1 and 2, respectively).

6.1.3 Appliance 2

Single-hob measurement using the standard set of pots Figure 41 shows the B-field measured in the vicinity of appliance 2, with hob 2 switched on using pot 3 (standard set of pots) centered (front side measurement). The B-field does not exceed the ICNIRP limit (6.25 μT) for a measuring distance of 30 cm, according to EN50366. The limit is not even exceeded at 1 cm off the edges of the appliance.

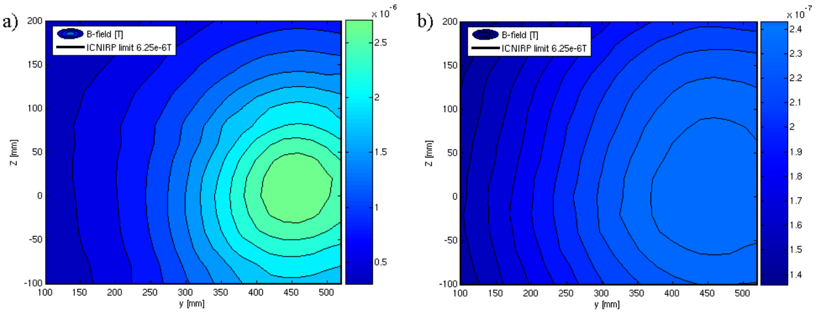


Figure 41: **Appliance 2, single-hob measurement using the standard set of pots:** Hob 2 (largest) is switched on, with pot 3 centered (front side measurement). The B-field was measured in the vertical plane (y, z) at measuring distances a) 1 cm and b) 30 cm; other measuring conditions according to EN50366.

Multi-hob measurement using the standard set of pots Figures 42 and 43 depict the B-field measured in the vicinity of appliance 2 (multi-hob measurement using the standard set of pots centered and non-centered, respectively) with hobs 1, 2, 3 and 4 simultaneously switched on (multi-hob measurement) using the standard set of pots (pots 14a, 3, 14b and 13 on hobs 1, 2, 3 and 4, respectively). The B-field does not exceed the ICNIRP limit (6.25 μT) for a measuring distance of 30 cm, according to EN50366.

However, the maximum rms-values of the B-field measured at the front side of the appliance are 2.5 μT and 8.5 μT for a centered and non centered pots, respectively (measuring distance of 1 cm, see Figures 42 a) and 43 a). Figures 42 c), e) and g) (pots centered) show that the ICNIRP limit is exceeded for a measuring distance of 1 to 5 cm. The corresponding maximum rms-values of the B-field measured are 13.5 μT, 9 μT and 7 μT for the rear, left and right sides of the appliance, respectively. Figure 43 also shows that when the pots are non-centered, the ICNIRP limit is exceeded for a measuring distance ranging from 1 to 5 cm.

Single-hob measurement using pot 8, worst-case set of pots Figure 44 shows the B-field measured in the vicinity of appliance 2 with hob 2 switched on (single-hob measurement) using the worst-case pot 8. The B-field does not exceed the ICNIRP limit (6.25 μT) for a measuring distance of 30 cm, according to EN50366.

Figures 44 a), (pot centered), e) and f) (pot non-centered) show that the ICNIRP limit is exceeded for measuring distances of 1 to 5 cm and 5 to 10 cm when the pot is centered and non-centered, respectively. The corresponding maximum rms-values of the B-field measured are 7.5 μT and 16 μT (measuring distance of 1 cm).

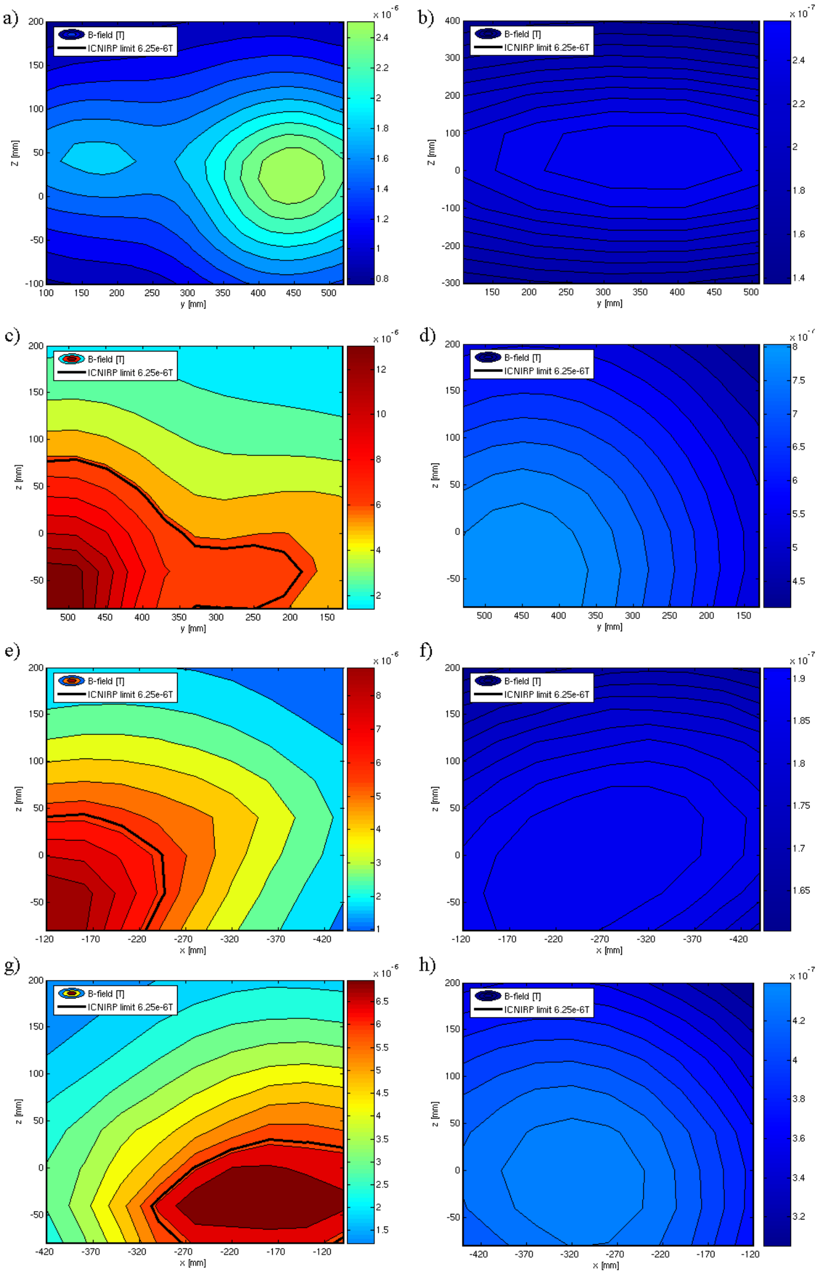


Figure 42: **Appliance 2, multi-hob measurement using the standard set of pots, with pots centered:** The *B*-field is measured in the vertical plane (y, z), at measuring distances of a), c), e) and g) 1 cm and b), d), f) and h) 30 cm; a) and b) front side, c) and d) rear side, e) and f) left side and g) and h) right side of the appliance. Hobs 1, 2, 3 and 4 are switched on simultaneously (multi-hob measurement) using the standard set of pots (pots 14a, 3, 14b and 13 on hobs 1, 2, 3 and 4, respectively); other measuring conditions according to EN50366.

Multi-hob measurement using the worst-case set of pots Figure 45 shows the *B*-field measured in the vicinity of appliance 2, with hobs 1, 2, and 3 switched on simultaneously (multi-hob measurement) using the worst-case set of pots (pots 7, 8 and 2 on hobs 1, 2 and 3,

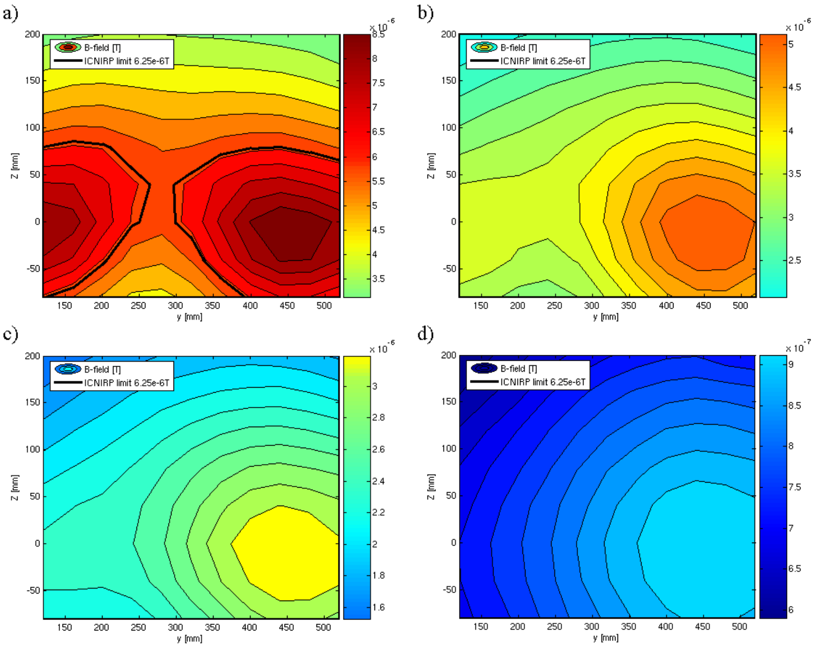


Figure 43: **Appliance 2, multi-hob measurement using the standard set of pots with pots non-centered (front side of the appliance):** The *B*-field is measured in the vertical plane (y, z), at measuring distances of a) 1 cm, b) 5 cm, c) 10 cm and d) 30cm. Hobs 1, 2, 3 and 4 are switched on simultaneously (multi-hob measurement), using the standard set of pots (pots 14a, 3, 14b and 13 on hobs 1, 2, 3 and 4, respectively); other measuring conditions according to EN50366.

respectively). The *B*-field does not exceed the ICNIRP limit (6.25 μT) for a measuring distance of 30 cm, according to EN50366.

Figure 45 a) (pots centered), as well as Figures e), f) and g) (pots non-centered) show that the ICNIRP limit is exceeded for a measuring distance from 1 to 5 cm and 10 cm for a centered and non-centered pots, respectively. The corresponding maximum rms-values of the *B*-field measured are 8.5 μT and 13.2 μT (measuring distance of 1 cm).

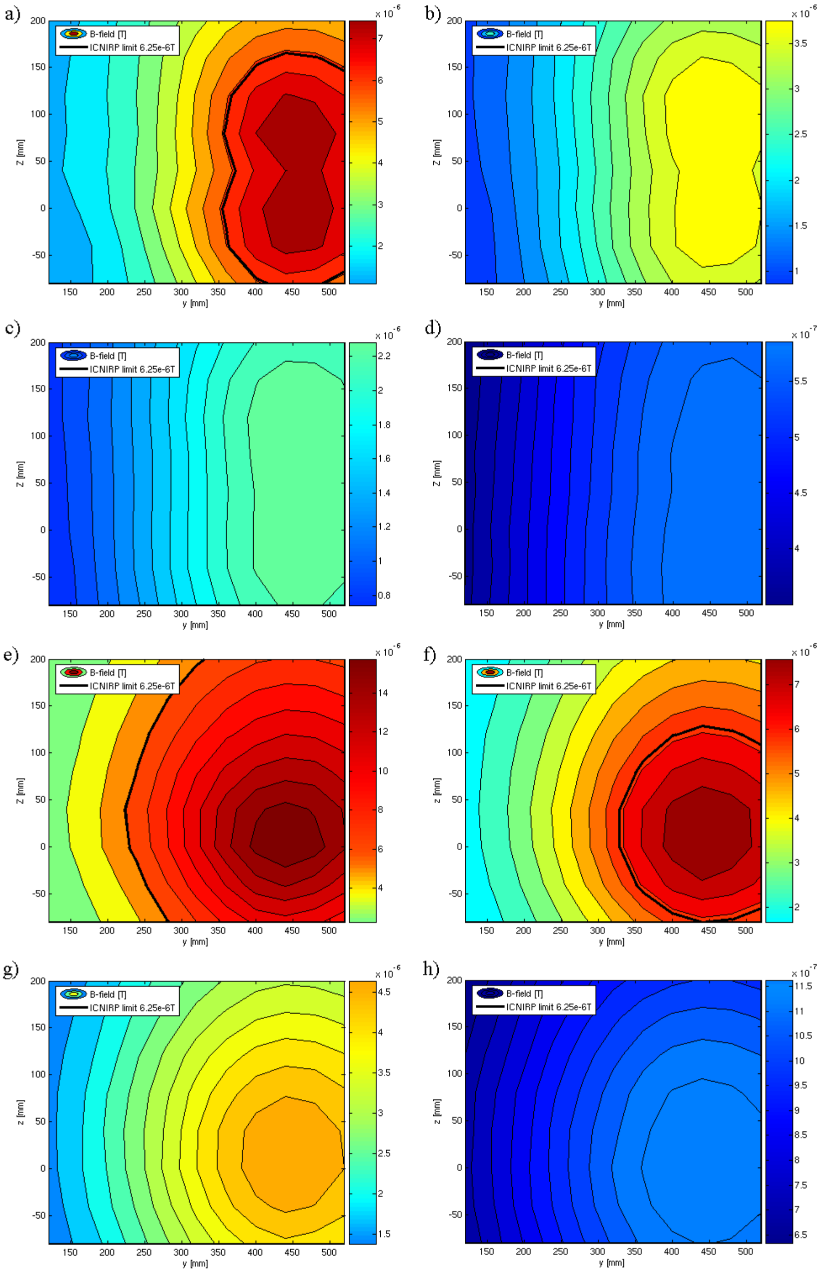


Figure 44: **Appliance 2, single-hob measurement using the worst-case set of pots. Comparison of the B-field when the pot are a) to d) centered, and e) to h) non-centered (front side of the appliance):** In Graphs a), b), c), d), e), f), g) and h), the B-field is measured in the vertical plane (y, z) at measuring distances of 1, 5, 10, 30, 1, 5, 10 and 30 cm, respectively. Hob 2 is switched on (single-hob measurement) using the worst-case pot 8.

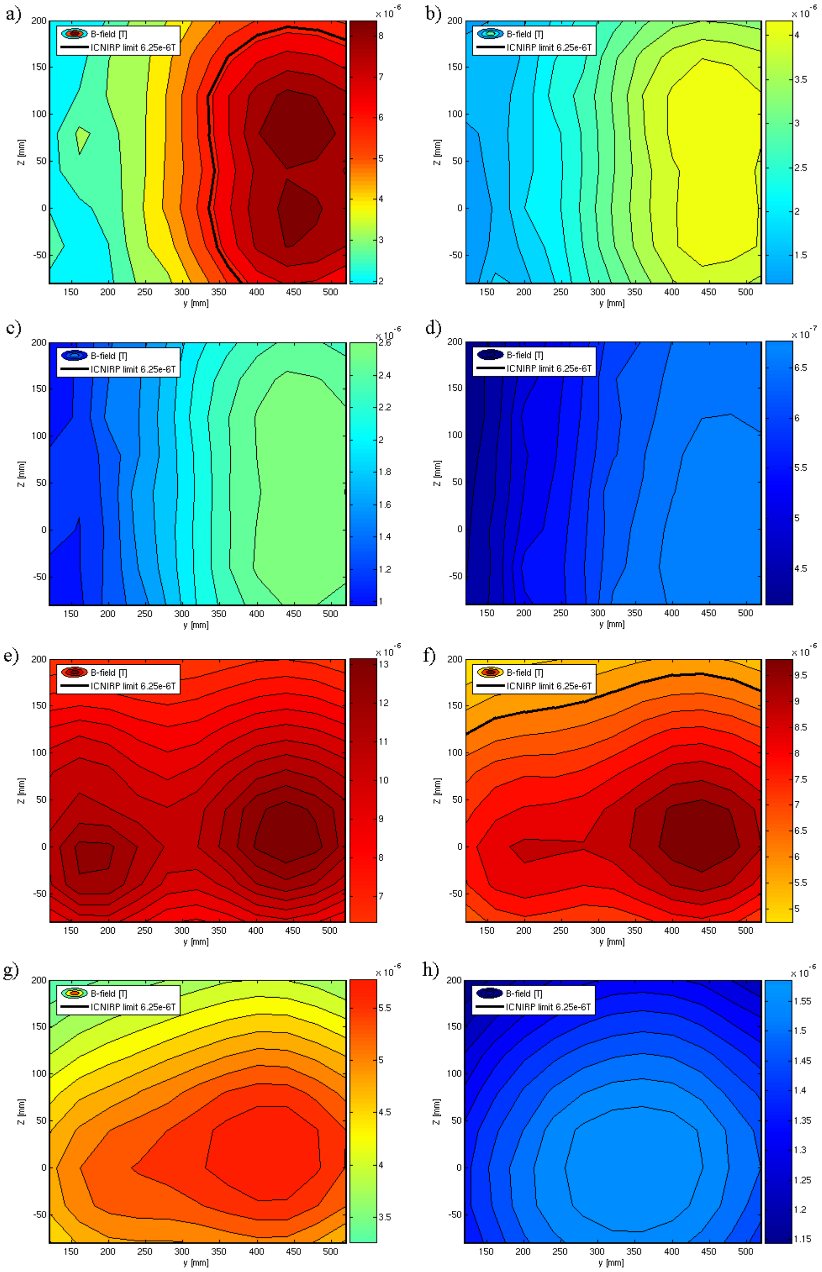


Figure 45: **Appliance 2, multi-hob measurement using the worst-case set of pots. Comparison of the B-field with the pot a) to d) centered, and e) to h) non-centered (front side of the appliance):** In Graphs a), b), c), d), e), f), g) and h), the B-field is measured in the vertical plane (y, z) at measuring distances of 1, 5, 10, 30, 1, 5, 10 and 30 cm, respectively. Hobs 1, 2, and 3 are switched on simultaneously (multi-hob measurement), using worst-case set of pots (pots 7, 8 and 2 on hobs 1, 2 and 3, respectively).

6.1.4 Appliance 3

Single-hob measurement using pot 3, large pot, standard set of pots Figures 46 and 47 depict the B-field measured in the vicinity of appliance 3 with pot 3 (large pot, standard set of pots) centered and non-centered. Figure 46 depicts the front side measurements, and Figure 47 the measurements at the rear, left and right sides of the appliance. The B-field does not exceed the ICNIRP limit (6.25 μT) for a measuring distance of 30 cm, according to EN50366.

However, at the front side of the appliance, Figures 46 f) and h) (pot non-centered) show that the ICNIRP limit is exceeded for a measuring distance of 12 cm. The maximum rms-values of the measured B-field are 3.7 μT and 18 μT (measuring distance of 1 cm) for a centered and non-centered pot, respectively. Moreover, Figure 47 shows that the ICNIRP limit is exceeded for a measuring distance of 5 cm, 4 cm and 3 cm for the rear, left and right sides of the appliance, respectively, when the pot is centered, and 14 cm, 14 cm and 13 cm for the rear, left and right sides of the appliance, respectively, when the pot is non-centered. The corresponding maximum rms-values of the B-field measured (measuring distance of 1 cm) are 12.5 μT, 11 μT, 9 μT (rear, left and right sides, pot centered) and 22.5 μT, 22.5 μT and 22 μT (rear, left and right sides, pot non-centered).

Single-hob measurement using pot 13, standard set of pots, small size Figures 48 and 49 show the B-field measured in the vicinity of appliance 3 with pot 13 (small pot, standard set of pots) centered and non-centered. Figure 48 depicts the front side measurements, and Figure 49 the measurements at the rear, left and right sides of the appliance. The B-field does not exceed the ICNIRP limit (6.25 μT) for a measuring distance of 30 cm, according to EN50366.

However, at the front side of the appliance, Figures 48 a) and e) (pot centered), as well as a f) and h) (pot non-centered) show that the ICNIRP limit is exceeded for a measuring distance of 4 cm and 19 cm for a centered and non-centered pot, respectively. The maximum rms-values of the B-field measured are 9 μT and 34 μT (measuring distance of 1 cm) for a centered and non-centered pot. Moreover, Figure 49 shows that the ICNIRP limit is exceeded for measuring distances of 10 cm, 9 cm and 10 cm for the rear, left and right sides of the appliance, respectively when the pot is centered, and 24 cm, 24 cm and 25 cm for the rear, left and right sides of the appliance, respectively, when the pot is non-centered. The corresponding maximum rms-values of the B-field measured (measuring distance of 1 cm) are 24 μT, 24 μT, 25 μT (rear, left and right sides, pot centered) and 51 μT, 55 μT and 57 μT (rear, left and right sides, pot non-centered).

Single-hob measurement using pot 8, worst-case set of pots Figures 50 and 51 depict the B-field measured in the vicinity of appliance 3 with pot 8 (worst-case set of pots) centered and non-centered. Figure 50 depicts the front side measurements, and Figure 51 the measurements at the rear, left and right sides of the appliance. The B-field does not exceed the ICNIRP limit (6.25 μT) for a measuring distance of 30 cm, according to EN50366.

However, at the front side of the appliance, Figures 50 a), b) and e) (pot centered), as well as f) and h) (pot non-centered) show that the ICNIRP limit is exceeded for a measuring distance of 6 cm and 20 cm for a centered and non-centered pot, respectively. The maximum rms-values of the B-field measured are 11.5 μT and 35 μT (measuring distance of 1 cm) for a centered and non-centered pot. Moreover, Figure 51 shows that the ICNIRP limit is exceeded for measuring distances of 13 cm, 13 cm and 14 cm for the rear, left and right sides of the appliance, respectively, when the pot is centered, and 22 cm, 24 cm and 24 cm for the rear, left and right sides of the appliance, respectively, when the pot is non-centered. The corresponding maximum rms-values of the measured B-field (measuring distance of 1 cm) are 30 μT, 30 μT, 34 μT (rear, left and right

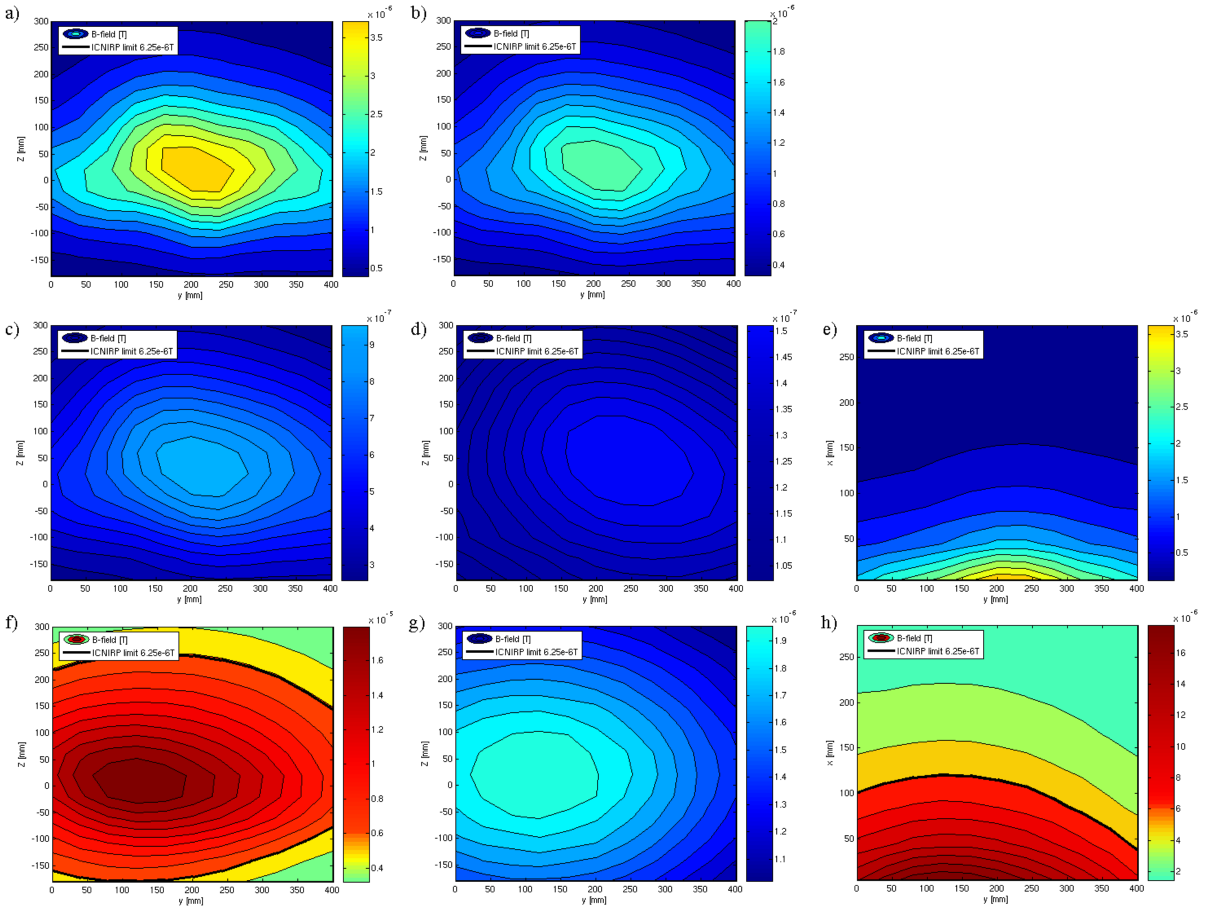


Figure 46: **Appliance 3 and pot 3 (large pot, standard set of pots), front side of the appliance. Comparison of the B-field with pot a) to e) centered, and f) to h) non-centered:** In Graphs a), b), c), d), f) and g), the B-field is measured in the vertical plane (y, z), at measuring distances of 1, 5, 10, 30, 1 and 30 cm, respectively. In Graphs e) and h), the B-field is measured in the horizontal plane. Other measuring conditions according to EN50366.

sides, pot centered) and 50 μT, 60 μT and 60 μT (rear, left and right sides, pot non-centered).

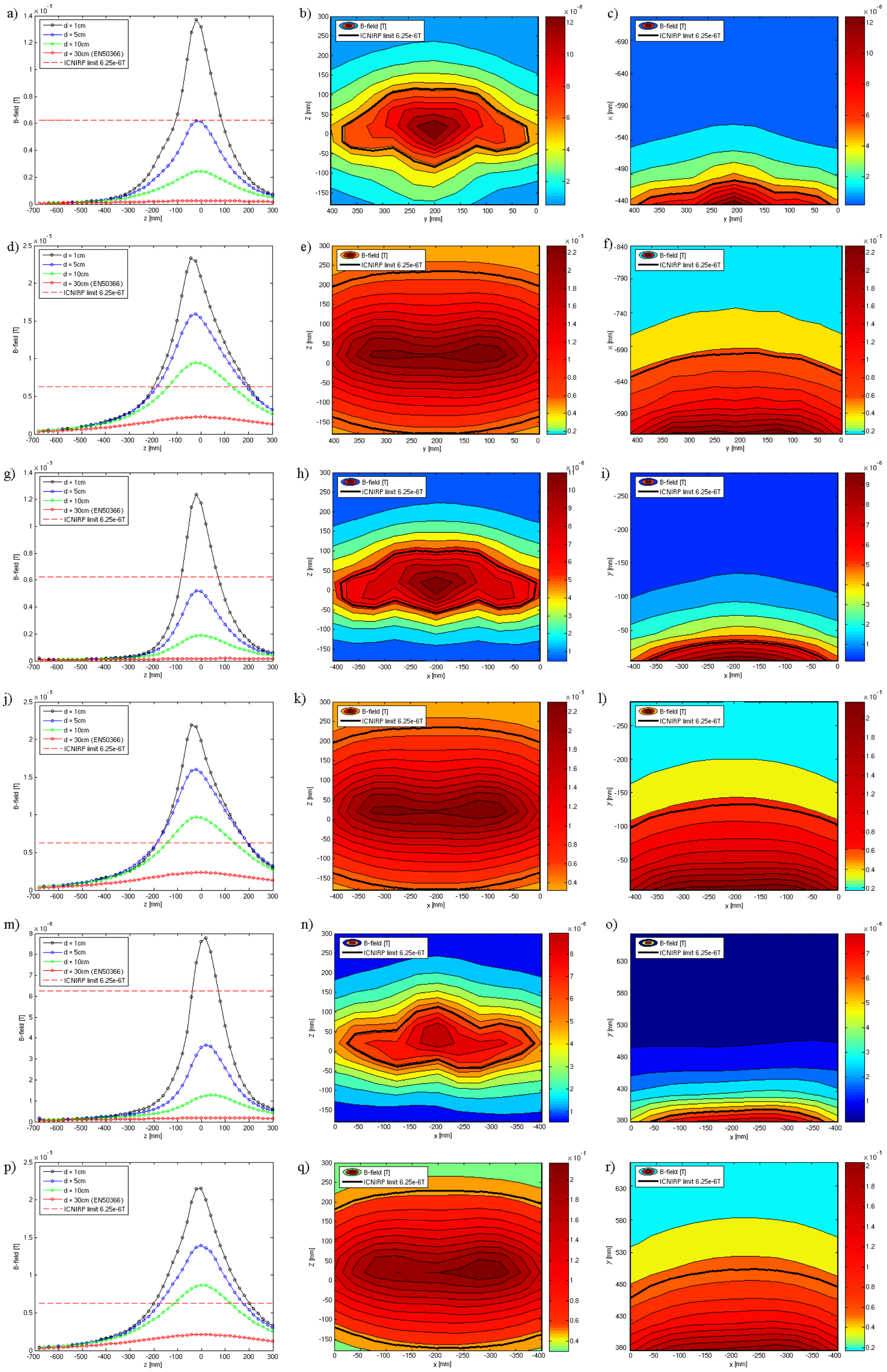


Figure 47: **Appliance 3 and pot 3 (large pot, standard set of pots). Graphs a) to f), g) to l) and m) to r) correspond to the rear, left and right sides of the appliance, respectively. Comparison of the *B*-field with pot a) to c), g) to i), m) to o) centered, and d) to f), j) to l) and p) to r) non-centered:** In Graphs a), d), g), j), m) and p), the *B*-field is measured along the z-axis at measuring distances of 30, 10, 5 and 1 cm. In Graphs b), e), h), k), n) and q), the *B*-field is measured in the vertical plane, at a measuring distance of 1 cm. In Graphs c), f), i), l) o) and r), the *B*-field is measured in the horizontal plane. Other measuring conditions according to EN50366.

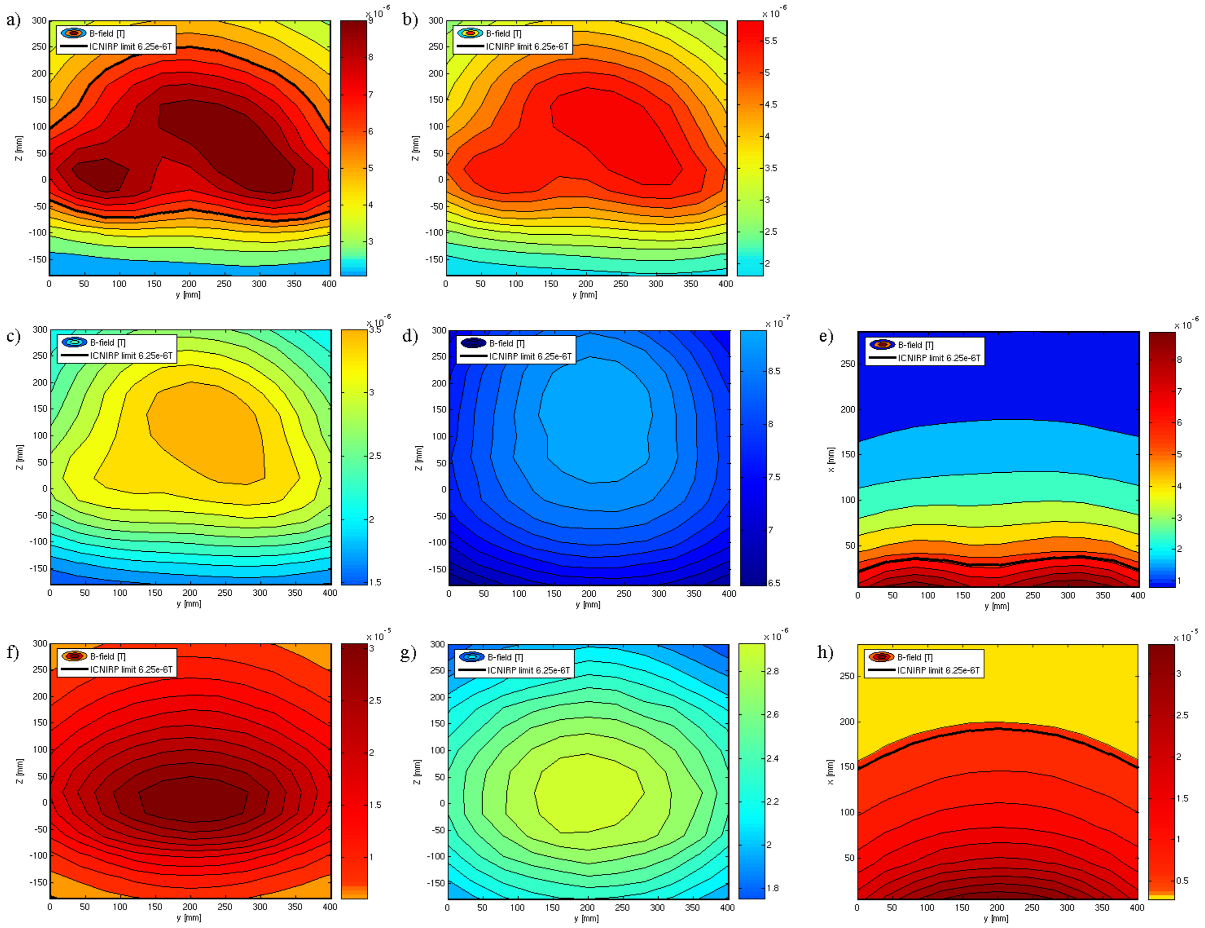


Figure 48: **Appliance 3 and pot 13 (small pot, standard set of pots), front side of the appliance. Comparison of the *B*-field with pot a) to e) centered, and f) to h) non-centered:** In Graphs a), b), c), d), f) and g), the *B*-field is measured in the vertical plane (y, z), at measuring distances of 1, 5, 10, 30, 1 and 30 cm, respectively. In Graphs e) and h), the *B*-field is measured in the horizontal plane. Other measuring conditions according to EN50366.

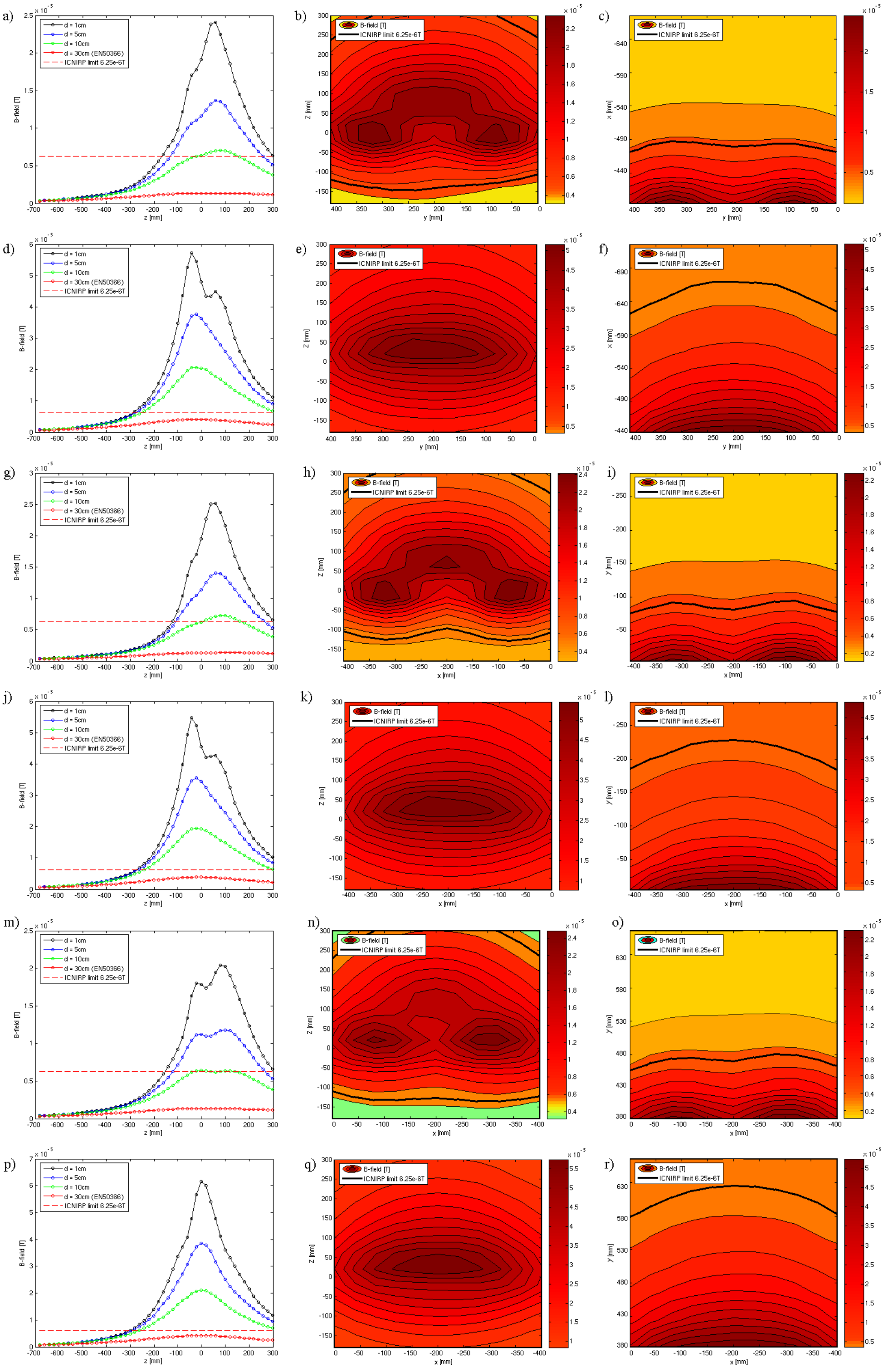


Figure 49: **Appliance 3 and pot 13 (small pot, standard set of pots). Graphs a) to f), g) to l) and m) to r) correspond to the rear, left and right sides of the appliance, respectively. Comparison of the *B*-field with pot a) to c), g) to i), m) to o) centered, and d) to f), j) to l) and p) to r) non-centered:** In Graphs a), d), g), j), m) and p), the *B*-field is measured along the z-axis at measuring distances of 30, 10, 5 and 1 cm. In Graphs b), e), h), k), n) and q), the *B*-field is measured in the vertical plane, at a measuring distance of 1 cm. In Graphs c), f), i), l) o) and r), the *B*-field is measured in the horizontal plane. Other measuring conditions according to EN50366.

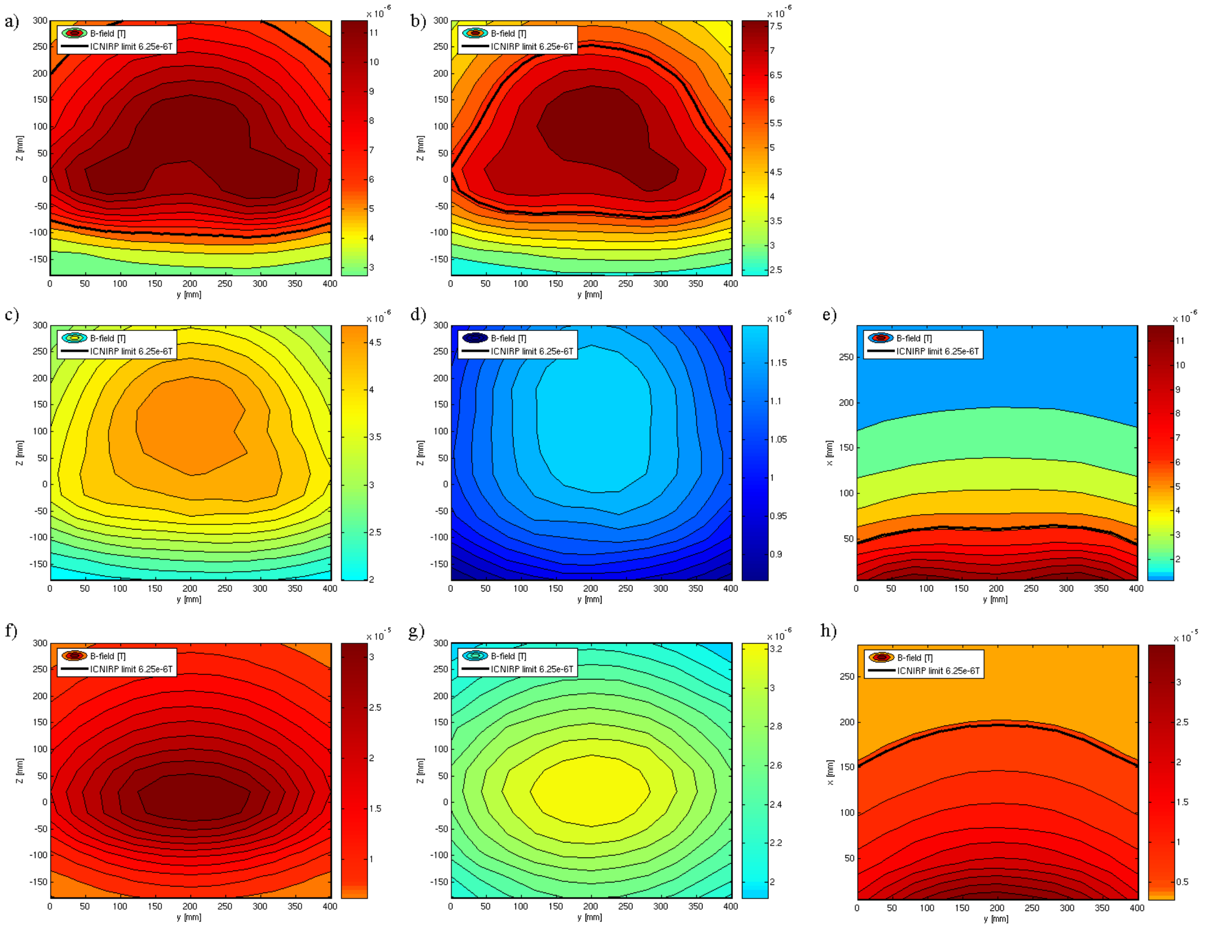


Figure 50: **Appliance 3 and pot 8 (worst-case set of pots), front side of the appliance. Comparison of the *B*-field with pot a) to e) centered, and f) to h) non-centered:** In Graphs a), b), c), d), f) and g), the *B*-field is measured in the vertical plane (y, z), at measuring distances of 1, 5, 10, 30, 1 and 30 cm, respectively. In Graphs e) and h), the *B*-field is measured in the horizontal plane.

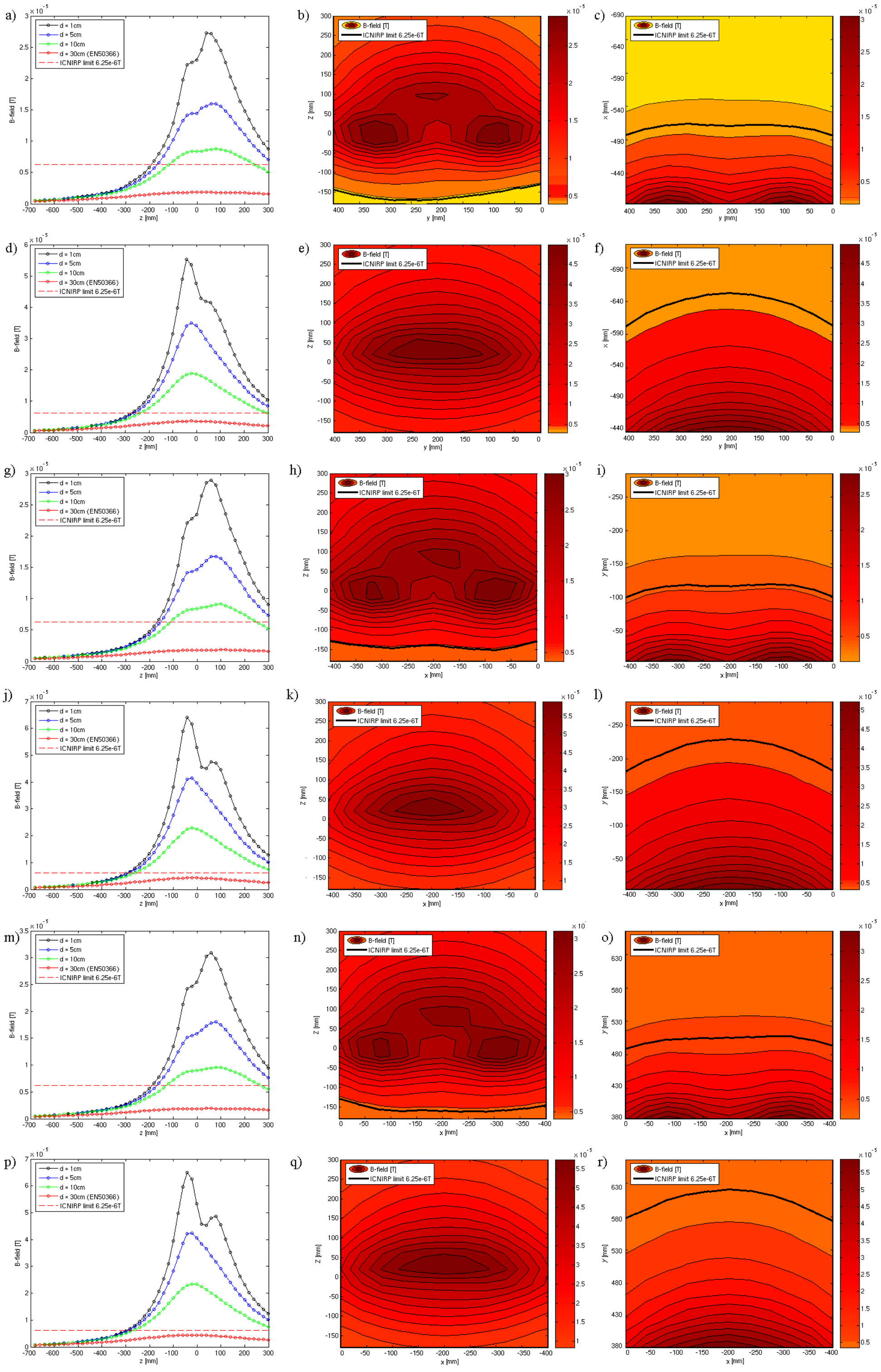


Figure 51: **Appliance 3 and pot 8 (worst-case set of pots). Graphs a) to f), g) to l) and m) to r) correspond to the rear, left and right sides of the appliance, respectively. Comparison of the *B*-field with pot a) to c), g) to i), m) to o) centered, and d) to f), j) to l) and p) to r) non-centered:** In Graphs a), d), g), j), m) and p), the *B*-field is measured along the z-axis at measuring distances of 30, 10, 5 and 1 cm. In Graphs b), e), h), k), n) and q), the *B*-field is measured in the vertical plane, at a measuring distance of 1 cm. In Graphs c), f), i), l) o) and r), the *B*-field is measured in the horizontal plane.

6.1.5 B-field Measurement Above the Appliances

As indicated in Figure 52, the B-field was measured above the induction cookers to evaluate the exposure in the vicinity of the pot.

With induction cookers, the surroundings of the hob do not heat significantly, allowing the cook to stay in the vicinity of the cooking area, where the magnetic field exposure is at a maximum.

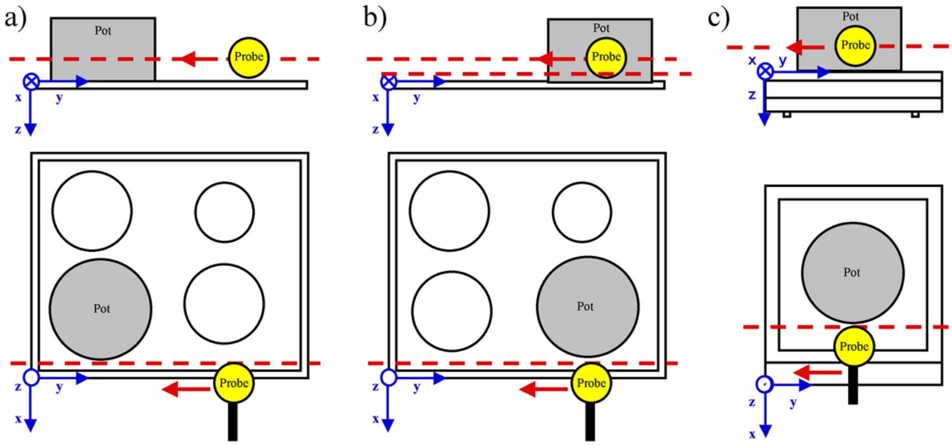


Figure 52: **Description of the B-field measurement above a) appliance 1, b) appliance 2 and c) appliance 3:** The probe measures the B-field along the horizontal y-axis, at the front sides of the appliances (single-hob measurements, with pots 3, 8 and 13 centered on the hobs).

The B-fields measured above the three appliances are given in Figure 53. The maximum rms-values measured are $9.3\,\mu$T and $47\,\mu$T for pots 3 and 8, respectively (appliance 1), $9.5\,\mu$T and $61\,\mu$T for pots 3 and 8, respectively (appliance 2), and $55\,\mu$T, $80\,\mu$T and $84\,\mu$T for pots 3, 13 and 8, respectively (appliance 3). These values exceed the ICNIRP guidelines by a factor of 1.5, 7.5, 1.5, 9.8, 8.8, 12.8 and 13.4, respectively.

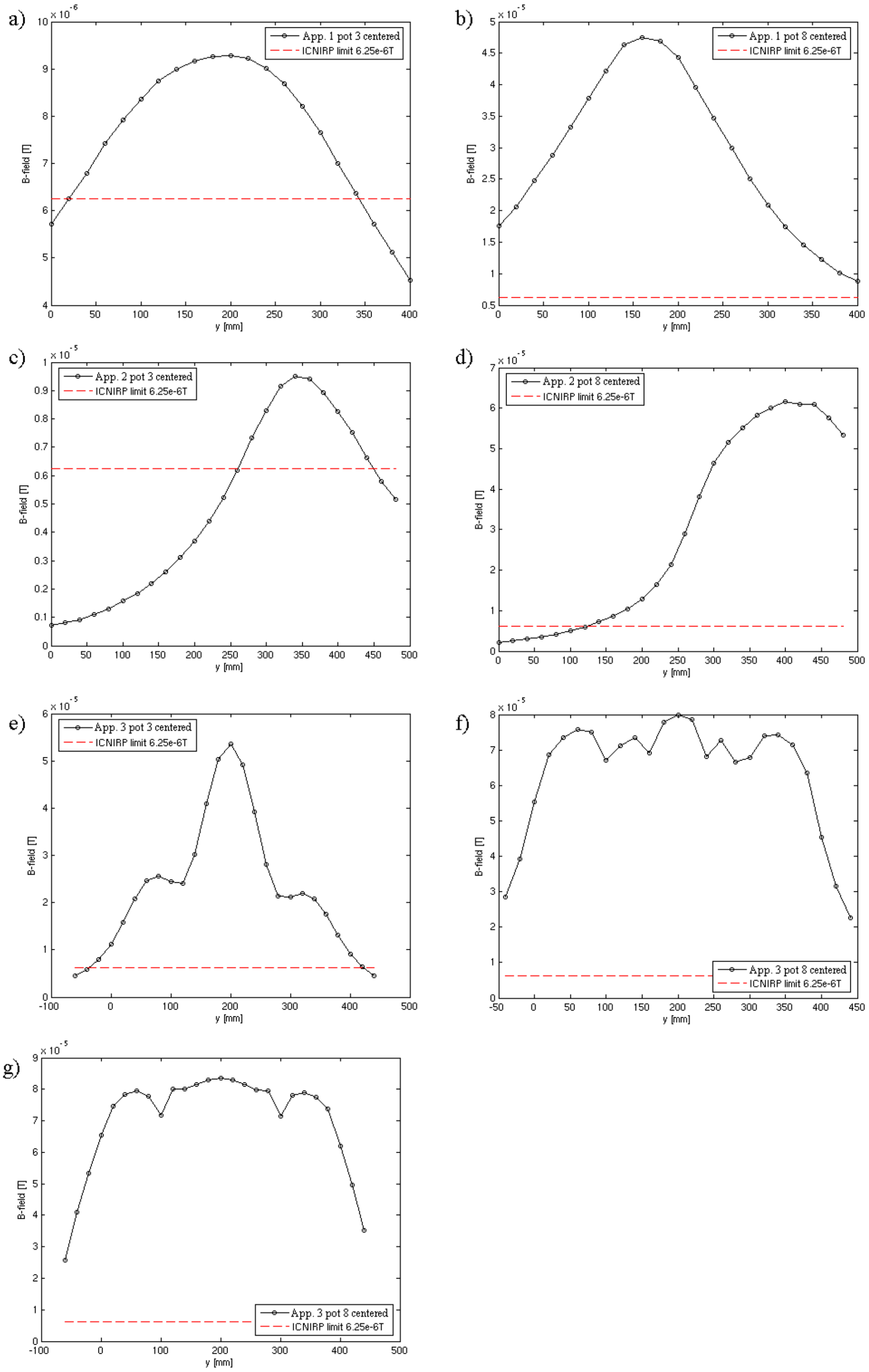


Figure 53: ***B*-field measurement above the appliances:** a) and b) correspond to appliance 1, with a) pot 3 centered, b) pot 8 centered. c) and d) correspond to appliance 2, with c) pot 3 centered, d) pot 8 centered. e) to g) correspond to appliance 3, with e) pot 3 centered, f) pot 13 centered, and g) pot 8 centered. Measuring conditions are described in Chapter 6.1.1.

6.1.6 Discussion

The evaluation according to EN50366 (i.e., for a measuring distance of 30 cm) demonstrates compliance according to the ICNIRP limit (6.25 μT) for all three devices with a margin larger than 13 dB (see Chapter 5.0.1 and Table 11).

As demonstrated in this report, different pot and and heating configurations can results in exposures that well exceeds +10 dB of the standard EN50366 configurations at same distance. In addition, the field distribution has a strong gradient in the direction of larger distances (see Table 14).

The maximum distance at which the ICNIRP limit of 6.25 μT is exceeded is 25 cm for Appliance 3 (pots non-centered). At 1 cm the limit is exceed by almost 20 dB. When measuring above appliance 3 (single-hob measurement, pot 8 centered), the measured B-field exceeds this guideline by over 22 dB. Since the induced currents are a function of the exposed cross-section and not of local fields, these violations of the derived limits are not necessarily also a violation of the governing basic restrictions.

Table 14: Summary of the results discussed in Chapters 6.1.2, 6.1.3 and 6.1.4. The column "other sides" corresponds to the rear, left and right sides of the appliances.

Appliance	Set of pots	Measurement type	Pot(s) centered	Meas. dist. at which ICNIRP limit is exceeded		Max. *B*-field at meas. dist. of 1 cm		Max. *B*-field at meas. dist. of 5 cm	Max. *B*-field at meas. dist. of 10 cm	Max. *B*-field of meas. at 30 cm	Comparison of meas. at dist. 30 cm and ICNIRP limit	Comparison of meas. at dist. 30 cm and 1 cm
				front side [cm]	other sides [cm]	front side [μT]	front side [μT]	front side [μT]	front sides [μT]	front side [μT]	[dB]	[dB]
Appliance 1	Standard	Single-hob	yes	3	3	7.2	8.0	3.0	1.4	0.21	-29	31†
			no	5.5	-	13	-	7.4	3.5	1.0	-15.9	22†
	Standard	Multi-hob	yes	1-5	-	8.6	-	3.7	1.9	0.39	-24	27†
			no	5-10	-	13	-	6.4	4.2	1.1	-15.1	21†
	Worst-case	Single-hob	yes	9	-	21	-	10	5.6	1.0	-15.9	26†
			no	15	-	38	-	18	9.9	1.8	-10.8	26†
	Worst-case	Multi-hob	yes	9	-	21	-	9.7	5.1	1.0	-15.9	26†
			no	15	-	36	-	18	9.4	1.9	-10.3	26†
Appliance 2	Standard	Single-hob	yes	-	-	2.7	14	2.0	1.3	0.24	-28	21†
			no	-	-	-	-	-	-	-	-	-
	Standard	Multi-hob	yes	1-5	1-5	2.5	13.5	1.7	0.97	0.26	-28	19.7†
			no	1-5	-	8.5	-	5.4	3.4	0.94	-16.8	19.5†
	Worst-case	Single-hob	yes	1-5	-	7.5	-	4.6	2.4	0.61	-20	22†
			no	5-10	-	16	-	8.2	5.0	1.2	-14.3	22†
	Worst-case	Multi-hob	yes	1-5	-	8.5	-	4.5	2.8	0.68	-19.3	22†
			no	10	-	13.2	-	10	6.0	1.6	-11.8	18.3†
Appliance 3	Standard	Pot 3	yes	-	3-5	3.7	12.5	2.2	1.0	0.15	-32	38‡
			no	12	13-14	18	27.5	12	7.6	2.0	-10.1	23‡
	Standard	Pot 13	yes	4	9-10	9.0	25	6.2	3.7	0.91	-16.8	29‡
			no	19	24-25	34	57	23	13	2.9	-6.7	26‡
	Worst-case	Pot 8	yes	6	13-14	11.5	34	8.2	5.0	1.2	-14.3	29‡
			no	20	22-24	35	60	21	13	3.2	-5.8	25‡

Note:

† For the built-in type appliances 1 and 2 only front-side exposure values are compared, as only the exposure in front of the appliance is most relevant.

‡ For the free-standing appliance 3 exposure values from all sides (front and other sides) are compared as the device is accessible from all sides.

7 Approximation of Induced Current Density

As shown in Chapters 6.1.2, 6.1.3, 6.1.4 and in Table 14, the B-fields measured around the induction cookers are largely non-uniform.

The ICNIRP guidelines [2] state that the reference levels are intended to be spatially averaged values over the entire body of the exposed individual, but with the important provision that the basic restrictions on localized exposure are not exceeded. However, reliable estimations of the current density J induced in the body at close proximity to the induction cookers can only be obtained by appropriate simulation tools. Since these evaluations were not within the scope of this project, we approximate J based on very simple models in order to identify possible concerns of strong violations of the basic restrictions.

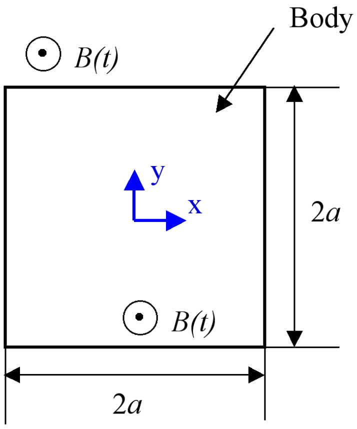


Figure 54: Magnetic field model used to roughly calculate the induced current density J in the body at close proximity to the induction cookers. The B-field does not depend on the position.

The magnetic field model shown in Figure 54 was used to roughly evaluate the induced current density J. The model assumes that the body has a homogeneous and isotropic conductivity, using a plane wave approximation of the B-field. The induced current density J is derived from Faraday's law of induction (simple circular conductive loop model, Equation (10)) and Ohm's law (Equation (11)):

$$\oint_L \mathbf{E}\,\mathrm{d}\mathbf{l} = -\int_S \frac{\partial \mathbf{B}}{\partial t} \cdot \mathrm{d}\mathbf{A} \tag{10}$$

$$\mathbf{J} = \sigma \mathbf{E} \tag{11}$$

where $\mathbf{E}$ and $\mathbf{B}$ are the electric and magnetic fields, L and S are the contour and the surface, and $\mathbf{J}$ and σ are the current density and the conductivity, respectively.

In this model, B does not depend on the position (see Figure 54). The B-field is given by $\mathbf{B}(\mathbf{x},\mathbf{y},\mathbf{z},t) = B(\mathbf{z},t) = B_0 \sin(\omega t)$, with $\omega = 2\pi f$ the angular velocity. The electric field E is derived from Faraday's law for a pure sinusoidal field at frequency f:

$$\oint_L \mathbf{E}\,\mathrm{d}\mathbf{l} = 8aE(t) \tag{12}$$

$$-\int_S \frac{\partial \mathbf{B}}{\partial t} \cdot \mathrm{d}\mathbf{A} = 4a^2 B_0\, \omega \cos(\omega t) \tag{13}$$

$$\mid E(t) \mid \quad = \quad \pi a f B_0 \tag{14}$$

The induced current density J is derived from Ohm's law:

$$\mid J(t) \mid = \pi a f \sigma B_0 \tag{15}$$

The averaged B-field for the worst-case configuration of Appliance 3, averaged over the area with $a = 0.175m$ (dimensions of the numerical homogeneous human body, see [4]) at height $z = 1\,\mathrm{m}$, equals $18\,\mu\mathrm{T}$ (average B-field in the worst case plane). Assuming $f = 20\,\mathrm{kHz}$, $\sigma = 0.2\,\mathrm{S/m}$ (see [2]), the induced current density magnitude equals $J = 39.6\,\mathrm{mA}/m^2$ (rms) compared to the ICNIRP basic restriction for the general public exposure at 20 kHz, which equals $40\,\mathrm{mA}/m^2$ (rms). A device with similar field distributions but close to the limits at EN50366 configurations (B=6.25 μT at a measuring distance of 30 cm, for standard measurement according to EN50366) would induce a current density of $315\,mA/m^2$, which would be 18 dB above the ICNIRP limits.

In conclusion, the ICNIRP basic restriction may be exceeded by considerable margin while the device would be considered compliant with EN50366. Further numerical simulations are therefore necessary to evaluate the potential of violation, especially in pregnant women.

8 Conclusion

The objective of this study was to assess the maximum exposure that arises during the use of induction cooking devices. Three devices currently available on the Swiss market were selected: the built-in appliances 1 and 2 (Electrolux GK58TCi and Gaggenau CI 261 110) and the portable appliance 3 (Inducs SH/BA 5000). The appliances were mounted on wooden supports allowing measurement in close proximity to the hobs without disturbing the B-field.

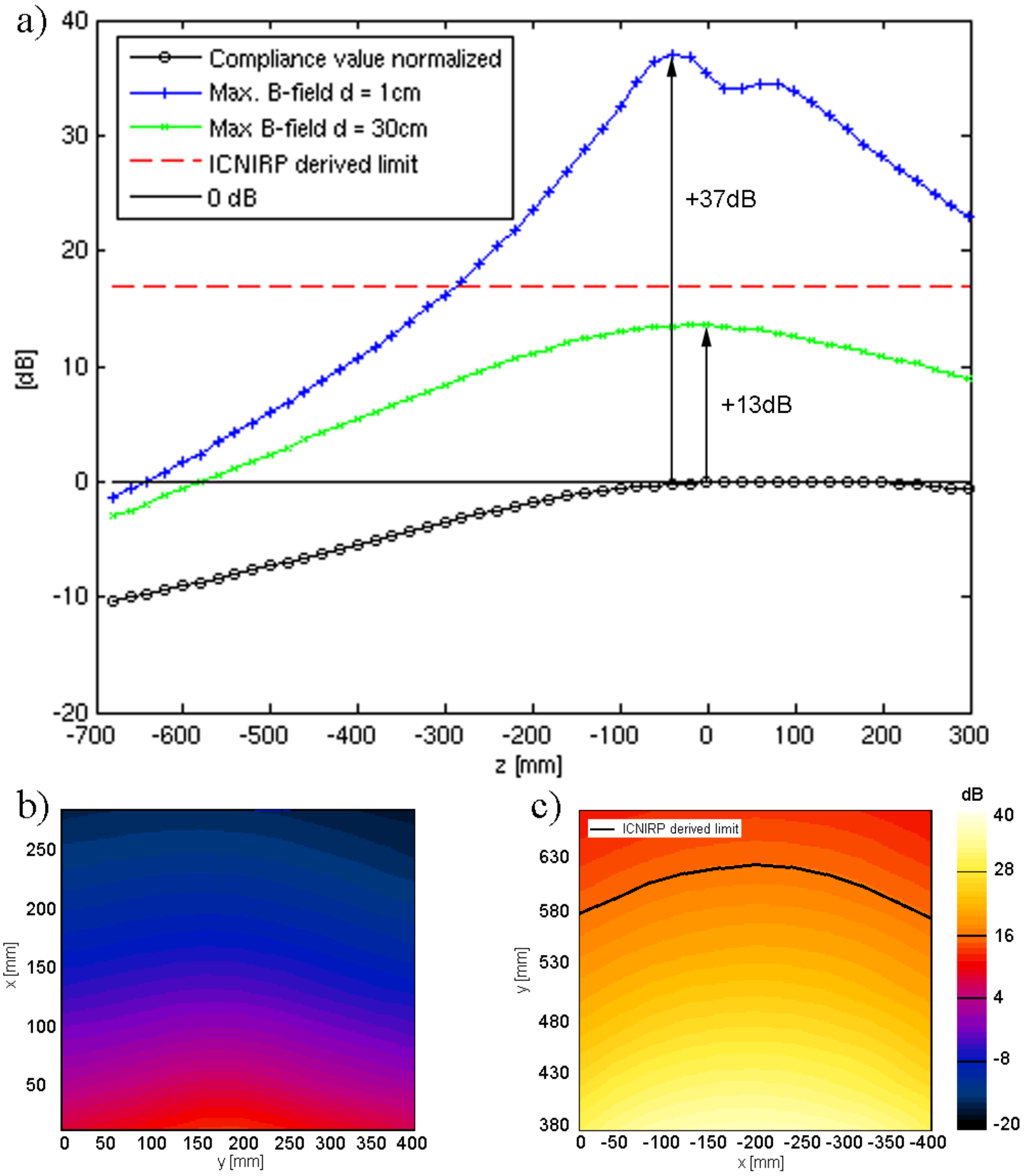


Figure 55: a) Comparison between the compliance value (B-field measured according to EN50366) and the maximum B-field measured in the worst-case scenarios at 1 cm and 30 cm of Appliance 3. b) B-field measured according to EN50366 and c) B-field measured in the worst-case configuration (horizontal plane at height of appliance).

Fifteen pots and pans of different sizes and shapes, as well as of various materials were evaluated in single and multi-hob use in order to select a worst-case set of pots corresponding to the worst-case B-field exposure. A standard set of pots was also defined according to the European Norm EN50366. The Narda probe ELT-400 specifications were validated, and the probe was used for the characterization of the induction cookers in the time- and frequency-domains (cooking signal frequency, dependency on the heat setting, contribution).

In the first step, the spatial B-field exposure was evaluated according to EN50366 [4] (i.e., at a measuring distance of 30 cm using the standard set of pots). All three appliances met the compliance criteria of ICNIRP [2] for incident B-fields by a margin larger than 14 dB (see Table 11).

In the second step, the worst-case exposure was evaluated as a function of pot and heating configurations. It was demonstrated that different pot and and heating configurations can result in exposures that well exceed +10 dB of the standard EN50366 configurations at the same distance (see Figure 55). In addition, the field distribution has a strong negative gradient in the direction of larger distances. Therefore, DASY4 was enhanced to enable 3D field scanning using the NARDA probe. At the very short distance of 1 cm, the fields can be more than 30 dB larger than at 30 cm (see Table 14). Combining the results from worst-case configurations and short distance measurements, the standard EN50366 values can be exceeded by 37 dB (see Figure 55). The uncertainty of the evaluation was determined to be ±1.5dB (k=2).

The third task was to evaluate the findings with respect to compliance testing. Assuming the distribution of Appliance 3, exposure close to the appliance could be as much as 37 dB or a factor of 70 above the ICNIRP safety limits. A very simple approximation suggest that the induced currents for such a worst-case compliant appliance would exceed the basic restrictions by nearly a factor of 10. In other words, the current standard EN50366 for compliance testing does not prevent exposures far above the basic restrictions and therefore needs revisions.

To obtain the scientific basis for a sound and reliable compliance test procedure, systematic evaluations of induced currents as a function of human anatomy and field distributions are necessary and recommended. The data obtained from this study indicates that an improved procedure will not be considerable more costly than EN50366.

9 Acknowledgments

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