HIGH SAR EXPOSURE OF 24 RATS AT 900 MHZ: PROBLEMS OF TEMPERATURE LIMITS AND UNIFORM FIELD DISTRIBUTION

J. Streckert[1], A. Bitz[1], V. Hansen[1], J. Buschmann[2]

[1]Chair of Electromagnetic Theory
University of Wuppertal
Gaussstrasse 20
42097 Wuppertal, Germany

[2]Fraunhofer Institute of Toxicology
Nikolai-Fuchs-Strasse 1
30625 Hannover, Germany

Abstract

Radial waveguide systems are suited for exposure of large numbers of samples at radio and microwave frequencies. An application of current interest is the investigation of biological effects on rodents being exposed ‘in vivo’ with mobile communication signals. A problem arises if the cross sectional dimensions of the waveguides must exceed half a wavelength as a consequence of the size of the biological objects. Then higher order waveguide modes are able to propagate contributing to uncontrollable fluctuations of the exposure field. Two concepts for suppressing the influence of disturbing modes in such cases are discussed. These measures were applied to an exposure system for experiments with 24 Wistar rats at 890 MHz. In a preliminary stage of the experiment the threshold between thermal and athermal region was determined. The criterion for defining the threshold was the measured body temperature of the rats. In order to apply SAR values close to the threshold an effective ventilation system had to be attached to the waveguide to avoid an environmental increase of heat due to the dissipation of rf energy through the animals.

I. Introduction

The steadily increasing use of mobile-frequency communication systems has raised public concerns on the question whether the corresponding pulse-modulated electromagnetic fields might cause adverse effects in the human organism, especially because the antennas of modern mobile telephones are located very close to the head and because the radiation from base stations is evidently distributed all over people’s living space. A recent study has amplified this concern: transgenic mice with additional copies of an oncogene showed significantly accelerated tumor development when exposed twice a day for 30 minutes to 900 MHz pulsed electromagnetic fields as compared to unexposed controls [1]. A reproduction study for this spectacular result has not yet been published by now and will indeed be difficult to perform because of the large spatial variability of the field distribution produced by the exposure system used in [1]. This leads to strong variations of the specific absorption rates (SAR) for the 100 exposed animals and thereby to a reduction of the statistical significance.

This example shows that the most important task is to expose each animal with identical fields and with it to produce the same SAR distribution inside each animal. It was already demonstrated in [2] that a low SAR deviation can be achieved by the use of a radial waveguide chamber of high circular symmetry with a central excitation, where the cages are arranged on a circle around the center (fig. 1). For investigations on melatonin synthesis of hamsters [3] a radial waveguide exposure system for 240 animals was set up, 120 of which were exposed with a typical 900 MHz mobile communication signal. All three of the hamsters could move freely inside their cages. In spite of this the overall SAR deviation was less than 30%. As the waveguide was operated with the fundamental mode, a precisely defined electromagnetic field yielding a high uniformity of the exposure could be guaranteed. Admittedly, this was also a result of a favourable relation of sample size (height of cages: 10 cm) to wavelength (c. 33 cm). If the biological design of an experiment prescribes a height of the cages that causes the waveguide dimensions to exceed half a wavelength, higher order modes may propagate, whose fields superpose the fundamental mode's field, thus causing unwanted perturbations and substantially larger SAR variations. In practice, this problem arises for example if larger biological objects like rats are exposed at 900 MHz. In case of the exposure with electromagnetic fields of high amplitude the absorption of the rf-power inside the rats body causes a rise in temperature of the animals surrounding space. In order to preclude a further increase of the rats body temperature by this non-electromagnetic heating, a ventilating system was installed. This paper will report on some substantial modifications of accustomed radial waveguide exposure systems in order to restrict the field variations to an acceptable degree in such cases and the design of the ventilating system.

II. Basics

As fig. 1 shows, a radial waveguide is an inhomogeneous waveguide which essentially consists of two circular parallel metal plates. In such a device TE^z_{mn}- und TM^z_{mn} - modes can exist. The index z shall remind of the fields' derivation from the potentials A_z and F_z [4, 5].
Especially the TM^z_{00}-mode is a TEM-mode with regard to the radial direction of propagation. The field components of the fundamental TEM-mode read:

$$E_\rho(\rho,\varphi,z) = E_\varphi(\rho,\varphi,z) = 0 \tag{1}$$

$$E_z(\rho,\varphi,z) = B_{00} H_0^{(2)}(k_0\rho) \tag{2}$$

$$H_\rho(\rho,\varphi,z) = H_z(\rho,\varphi,z) = 0 \tag{3}$$

$$H_\varphi(\rho,\varphi,z) = -jB_{00} H_0^{(2)}{}'(k_0\rho) \tag{4}$$

The electric field is polarized in z-direction and all field components of the TEM-mode are constant in z- and φ-direction. According to the behaviour of the Hankel function $H_0^{(2)}(k_0\rho)$ the fields decay approximately proportional to $1/\sqrt{\rho}$ for arguments $k_0\rho$ >> 1. The wave impedance is

$$Z = -jZ_0 \frac{H_0^{(2)}(k_0\rho)}{H_0^{(2)'}(k_0\rho)} \quad , \quad Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} \, . \tag{5}$$

For radii $\rho \geq \lambda_0$, the wave impedance is equal to the wave impedance Z_0 of a uniform plane wave in free space. All these characteristics show that the fundamental mode of the radial waveguide is ideally suited for achieving identical exposure conditions for many samples at a time.

The TEM-mode is able to propagate for any distance h of the metal plates. Higher order modes with an azimuthal dependence of the fields (~ cos(mφ) or ~ sin(mφ)) are not discussed here, because they are avoided by a rotationally symmetric excitation. But, for distances $h \geq \frac{\lambda}{2}$ the propagation of higher order TE- and TM-modes with respect to the z-coordinate is possible in addition to the fundamental mode. Their field components depend on z according to $\cos(k_z z)$ and $\sin(k_z z)$ with $k_z = \frac{n\pi}{h}$ $(n = 0,1,2,...)$. For instance, the components of the TM^z_{01}-mode are given by eqns. (6)-(10).

$$E_\rho(\rho, \varphi, z) = -B_{01} \frac{k_z}{k_\rho} H_0^{(2)}{}'(k_\rho \rho) \sin\left(\frac{\pi}{h} z\right) \tag{6}$$

$$E_\varphi(\rho, \varphi, z) = 0 \tag{7}$$

$$E_z(\rho, \varphi, z) = B_{01} H_0^{(2)}(k_\rho \rho) \cos\left(\frac{\pi}{h} z\right) \tag{8}$$

$$H_\rho(\rho, \varphi, z) = H_z(\rho, \varphi, z) \tag{9}$$

$$H_\varphi(\rho, \varphi, z) = -jB_{01} \frac{\omega\varepsilon}{k_\rho} H_0^{(2)}{}'(k_\rho \rho) \cos\left(\frac{\pi}{h} z\right) \tag{10}$$

III. Handling of higher-order modes

A selective exposure of moveable biological samples by one higher order radial waveguide mode, as it was proposed in [6] for experiments with rodents at 435 MHz, has at least two drawbacks: 1. The half-cosine distribution of the mode field implies additional posture-dependent variations of the exposure and 2. The potential of exciting the other possible modes is high, thus containing the risk of a randomly distributed exposure field. In biological experiments the preferred operating mode should be the fundamental TEM-mode for reasons of uniqueness of the exposure field. By combination of a small plate distance, a circularly symmetric excitation and an effective absorber at the outer boundary with uniform reflectivity it is possible to achieve a good power efficiency and a highly constant azimuthal field distribution that changes only slightly in radial direction. Fig. 2 shows an example for the calculated electric field at 900 MHz in a 90° sector of a radial waveguide of 4.5 m diameter and 14 cm plate distance which was used for the exposure of hamsters in [3]. At the boundary, a –20 dB absorber was built-in. The feeding was performed via a rotational symmetric cone antenna as sketched in fig. 1.

Any deviation from the waveguide's circularity decreases the rotational symmetry of the field pattern, but this is mainly a question of a careful implementation of the device. Much harder to prevent, however, are field perturbations that occur if higher order modes exist simultaneous to the fundamental mode. Due to different propagation constants the superposition of the modes results in rather complex spatial field distributions that depend sensitively on local tolerances of the waveguide geometry.

As mentioned before, higher order modes with a z–dependency are not able to propagate if the plate distance h is chosen electrically small, e.g. if $k < \pi / h$ holds. In order to match this condition, in an air-filled waveguide the height may not exceed appr. 16.7 cm at 900 MHz, for instance.

Indeed, a waveguide should never be operated exactly at the frequency according to this 'cutoff height', because of two reasons: 1. The dielectric properties of biological objects cause a certain drop of the cutoff frequency, and 2. higher order modes do not vanish abruptly below their cutoff frequency, but have evanescent fields and may contribute to field distortions if they are excited at discontinuities inside the waveguide.

In a new experiment with rats at 890 MHz, the plate distance of the radial waveguides had to be increased to 17 cm. This implies that, in principle, the modes with mode number n = 1 are able to propagate as well as the fundamental mode. They need to be suppressed in order to retain a uniquely defined exposure field. In order to achieve this, the following concepts were examined.

A. *Fundamental mode excitation of the exposure region*

For the z-component of the electric field of the $TM^{z}{}_{01}$-mode holds $E_z \sim \cos(\pi / h\, z)$ (Eq. 8), resulting in E_z values of equal amount, but opposite sign immediately at the plates. On the contrary, the TEM-mode is symmetrical with respect to z:

$$E_z(\rho,\varphi,z=0) = E_z(\rho,\varphi,z=h).$$

Similar relations are valid for the H_ρ components of the TE^z– and TEM–modes. An unsymmetric behaviour of the respective field is therefore a direct measure for the existence of higher order modes.

One possibility to avoid the excitation of higher order modes is a central feed shaped as a double-cone. Calculations and measurements yielded, however, that the demands for a symmetry of the whole exposure device with regard to the z-coordinate would be extremely high.

Instead of this, we favour a solution where the height of the radial waveguide is kept so small for low radii that only the fundamental mode can exist there, while a stepwise increase to the necessary height for inserting the cages follows immediately in front of the exposure region (fig. 3).

For such a configuration it turned out that even for larger radii no higher order modes are excited although the plate distance is bigger than half a wavelength. Thus, a very uniform and clearly defined excitation of the exposure region is achieved.

When the cages with the animals are put into the waveguide, one has to consider the scattering field emanating from the biological objects. As long as their size is small compared to the plate distance, the animals act only as local perturbations which do not influence each other, and the total field can be determined by numerical procedures on the basis of a suited animal model and the unique excitation field.

In experiments with large animals like rats, however, it might happen that an accidental adverse distribution of the objects generates a scattering field which causes an excitation of higher order modes. In order to avoid this further precautions should be taken, which are discussed in the following chapter.

B. *Up-shifting of cutoff frequencies*

A method known from microwave resonators in order to avoid undesired modes aims at shifting the cutoff frequencies of these modes outside the operating range by inserting dielectric bodies or by changing the geometry of the guiding structure.

Starting from the known fields of the undisturbed radial waveguide, various geometrical modifications were applied and compared by numerically solving the respective eigenvalue problem and by calculating the field distributions. An effective method which is rather easy to implement is to attach metal ribs to the upper and lower plates of the radial waveguide, which run between the cages from the central waveguide region to the absorber (fig. 4).

For the radial waveguide with 17 cm height a suitable choice of the ratios of rib height H to rib width W and of plate distance h to rib height H led to the result that the TE_{01}^{z}- und TM_{01}^{z}-modes, whose cutoff frequency is $f_c = c_0/(2h) = 882$ MHz in the waveguide without ribs, are effectively damped because their propagation constants k_ρ remain purely imaginary at the operating frequency of 890 MHz.

The total field within a cross section of the modified waveguide is only slightly changed compared to the original distribution of the fundamental TEM - mode (fig. 5). Between the upper and lower ribs, the electric field is increased, but across the exposure region, the field varies less and is linearly polarized in z-direction.

C. *Implemented exposure system*

For the exposure of 24 rats (1 per cage, rat's dimension: length 19 cm, ∅ 6 cm) at 890 MHz inside a radial waveguide with 4 m of diameter, $h_1 = 14$ cm, and $h_2 = 17$ cm the concept B was implemented in addition to concept A. This was necessary because of the large dimensions of the rats which might lead to field distortions and to the excitation of unwanted higher order modes due to the scattering field emanating from the rats. By an optimized ratio of width W and height H, this improved exposure chamber achieved an overall deviation of the electric field of about 13 % inside the entire exposure region.

It is expected that the field distribution of the empty waveguide is altered after insertion of the rats. As it is difficult to carry out reliable measurements of the field in an exposure device with moving test objects and even impossible to measure the field distribution inside the living animals, measurements with rat phantoms as well as extensive numerical computer simulations were performed in order to investigate the field disturbances caused by the biological objects. Fig. 6 shows the computed electrical field distribution of a 15°-sector at 890 MHz in the presence of a detailed rat-model which was derived from NMR-scans of a Wistar rat. The spatial resolution of the model is 1 mm^2 and 12 tissues are distinguished. The 15°-sector is bounded by magnetic walls in angular direction, with it a radial waveguide with 24 cages is simulated. It is confirmed that the field outside the rat has a good homogeneity across the exposure region and that the unavoidable perturbations which are introduced by the animal do not provoke an excitation of higher order modes. Results of measurements at the built-up 890 MHz device with and without inserted rat phantoms confirmed the stability of the exposure field [7].

In order to allow for illumination of the rodents and the supply with air openings were sawed in the upper metal plates above the cages which were closed by wire mesh lids. The shielding effectiveness of the wire mesh is about –50 dB. For reasons of easy disinfection of the cage region, it is separated from the other parts of the waveguide, e.g. containing the feed and the absorbers, by means of thin plastic walls fixed in front and behind the cages. The reflections at these walls are negligible. For the supply of water glass vertical tubes connected to an outer bottle are led to the cages through waveguides operated beyond cut off. Due to the high attenuation of the field strength inside these waveguides, these openings do not effect the shielding effectiveness of the exposure system.

IV. Temperature Measurements and Ventilation System

The particular biological design of the intended experiments implies an exposure of Wistar rats close to the onset of thermal effects, e.g. with power densities that give rise to an activation of the animal's thermoregulation system, but which remain just below the threshold for an elevation of the body temperature. Some people call this range of operation athermal in the sense of a three level classification distinguishing between non-thermal (no temperature rise, no thermoregulation), athermal (no temperature rise, thermoregulation) and thermal effects (temperature rise). As literature data show no clear agreement on the power density related to the athermal/thermal threshold, several experiments with different dosage levels were performed in a preliminary stage of the project. Taking into account that a value of 10 mW/cm^2 = 100 W/m^2 was found by Jensh [8] as a borderline for non-thermal exposure of rats at 915 MHz, we started from power densities of 10 W/m^2 and increased the level successively. Environmental and body temperature using rectal thermocouple tests were determined in every case. The data were taken from the exposed group as well as from the control group for different numbers of animals being housed in the respective radial waveguide. A first result was that between 50 and 60 W/m^2 the body temperature began to rise as compared to the values in the sham exposure unit. As the environmental temperature also increased with time, it was concluded that this must be due to a markedly built-up of heat within the waveguide with the exposed rats. It was decided to attach an effective ventilation system to the waveguides consisting of a central low-noise van and a symmetrically arranged system of 2 x 24 air pipes of 5 cm diameter which were connected to 5 cm holes in the lower waveguide plates under each cage. Thereby it could be achieved that the inside air temperature close to the rats differed no more from the temperature in the control group, regardless of the applied power densities. Moreover, below 65 W/m^2 no increase of body temperature could be identified. At 70 W/m^2 an average body temperature increase of 0.2 K was recorded, but without producing further environmental heating. Thus we conclude that the thermoregulation process of the Wistar rats works effectively up to power densities of 65 W/m^2 for 900 MHz. We chose a value of 60 W/m^2 for our further experiments. This corresponds to an averaged total input power of 203 W at a pulse duty cycle of the applied GSM modulation signal cocktail [9] of 7:8 and is equivalent in our exposure system to an average whole body SAR of 2.2 W/kg, which is a mean value for different postures and positions of the rats in their cages. The overall variation of the SAR was estimated as 35%.

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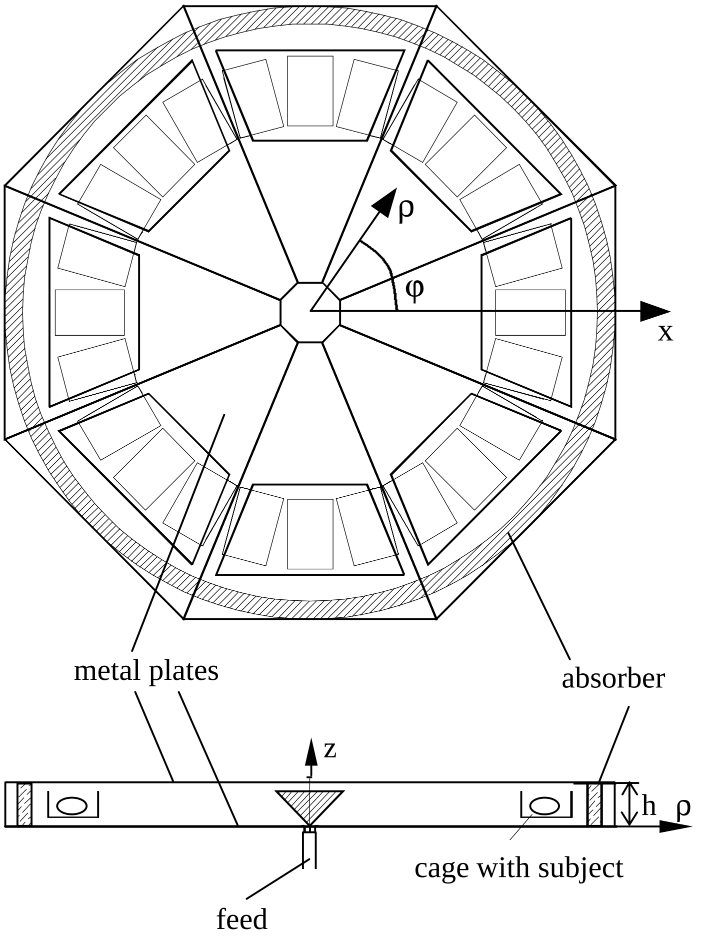

Fig 1: Top and side view of a radial waveguide system used for in vivo experiments

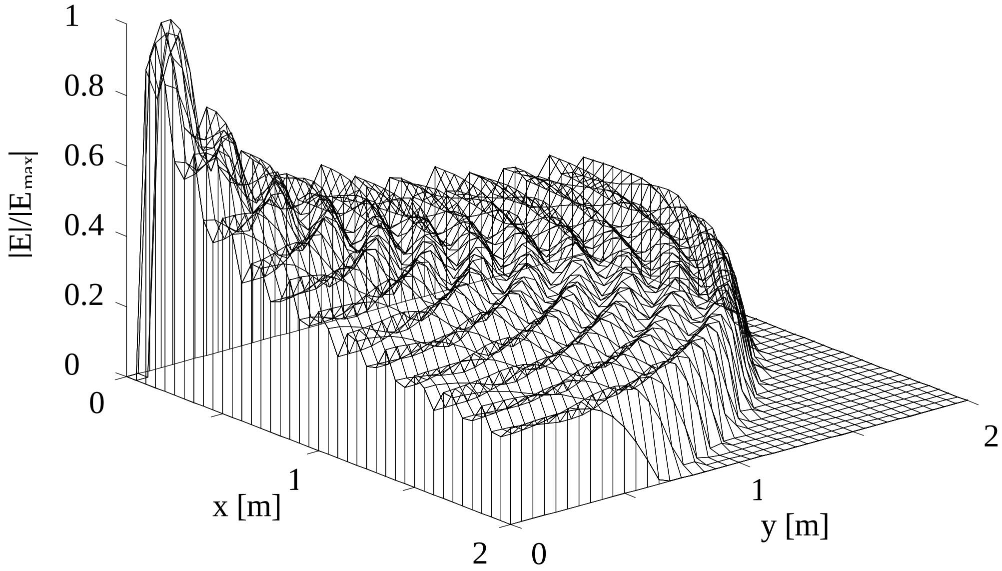

Fig. 2: Total electric field distribution inside a 90° sector of a radial waveguide at 900 MHz

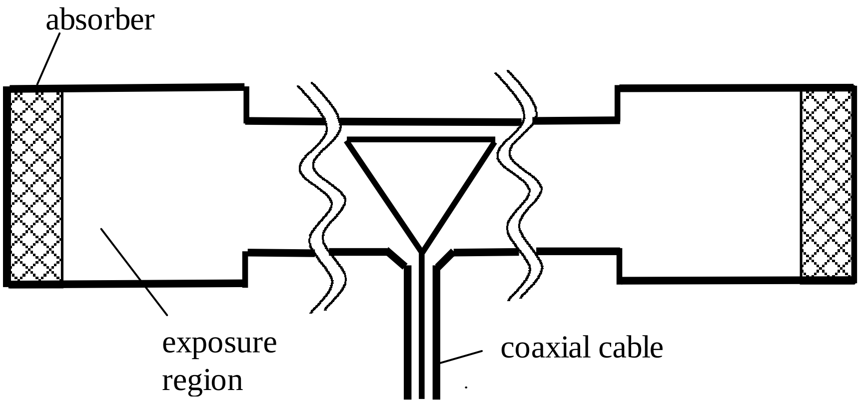

Fig. 3: Radial waveguide with stepwise change of cross section

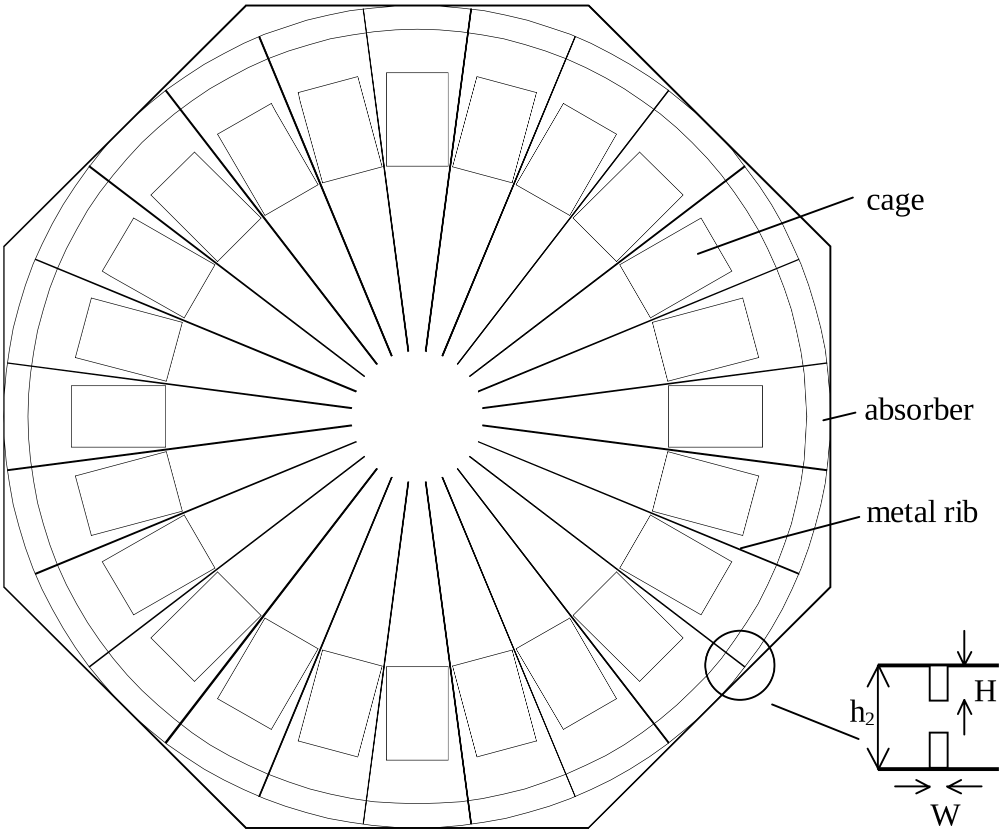

Fig. 4: Arrangement of metal ribs in the radial waveguide

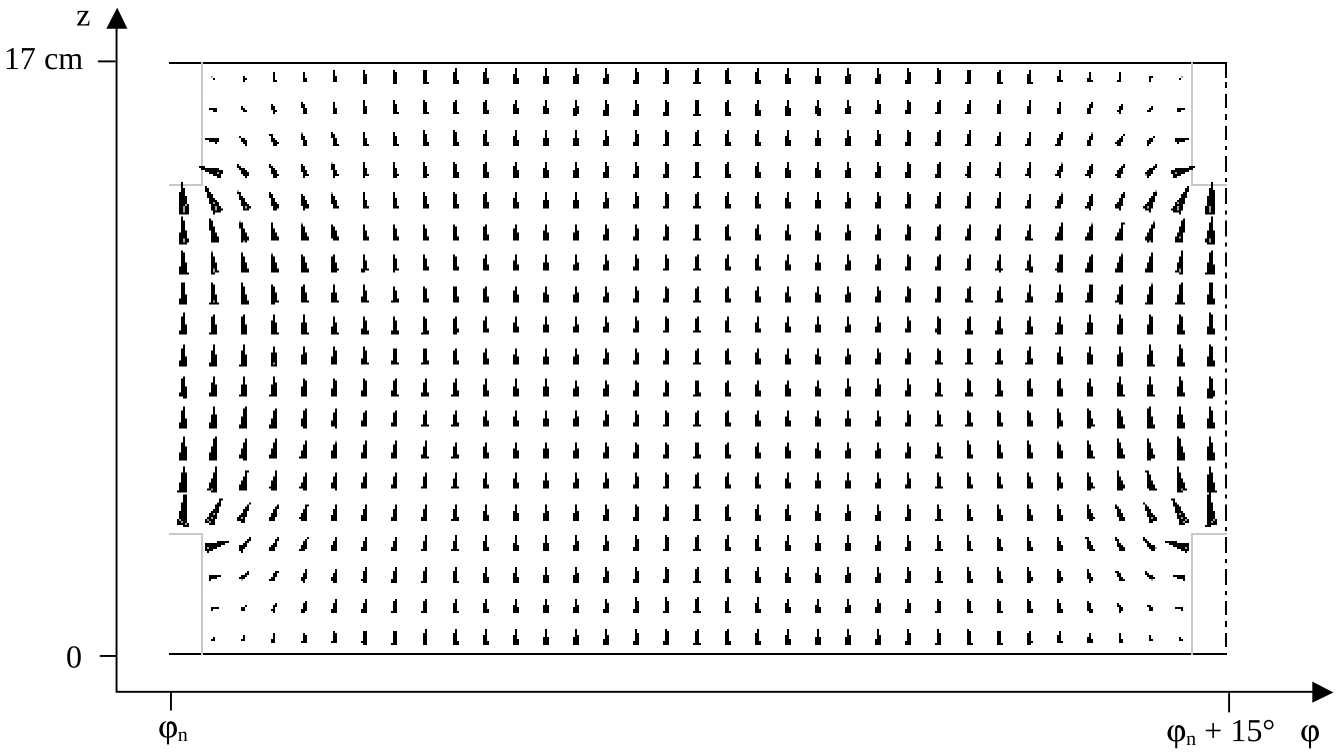

Fig. 5: Flux lines of the total electrical field in the cross section of one exposure region (cage region) of the empty radial waveguide with attached ribs (f = 890 MHz)

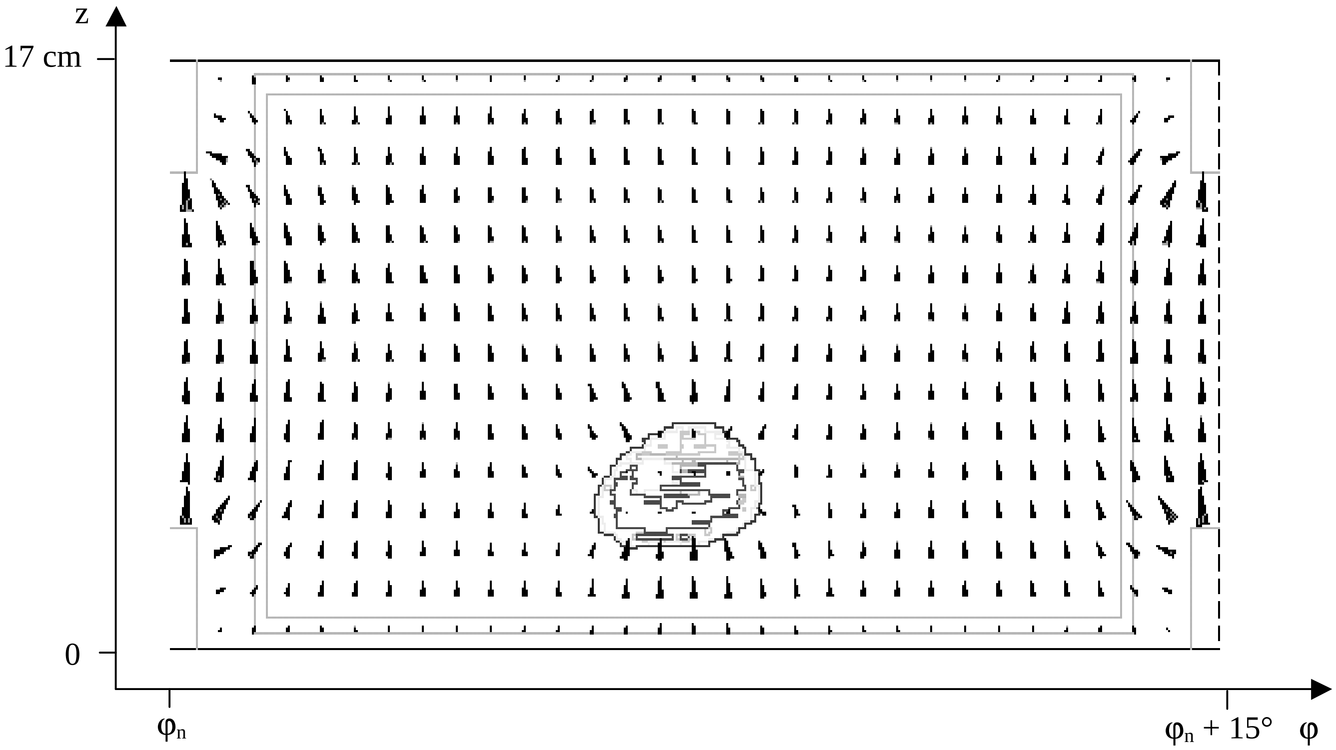

Fig. 6: Flux lines of the total electrical field in the cross section of one exposure region of the radial waveguide in the presence of a rat orientated in radial direction (f = 890 MHz)

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