High frequency electomagnetic field irradiation

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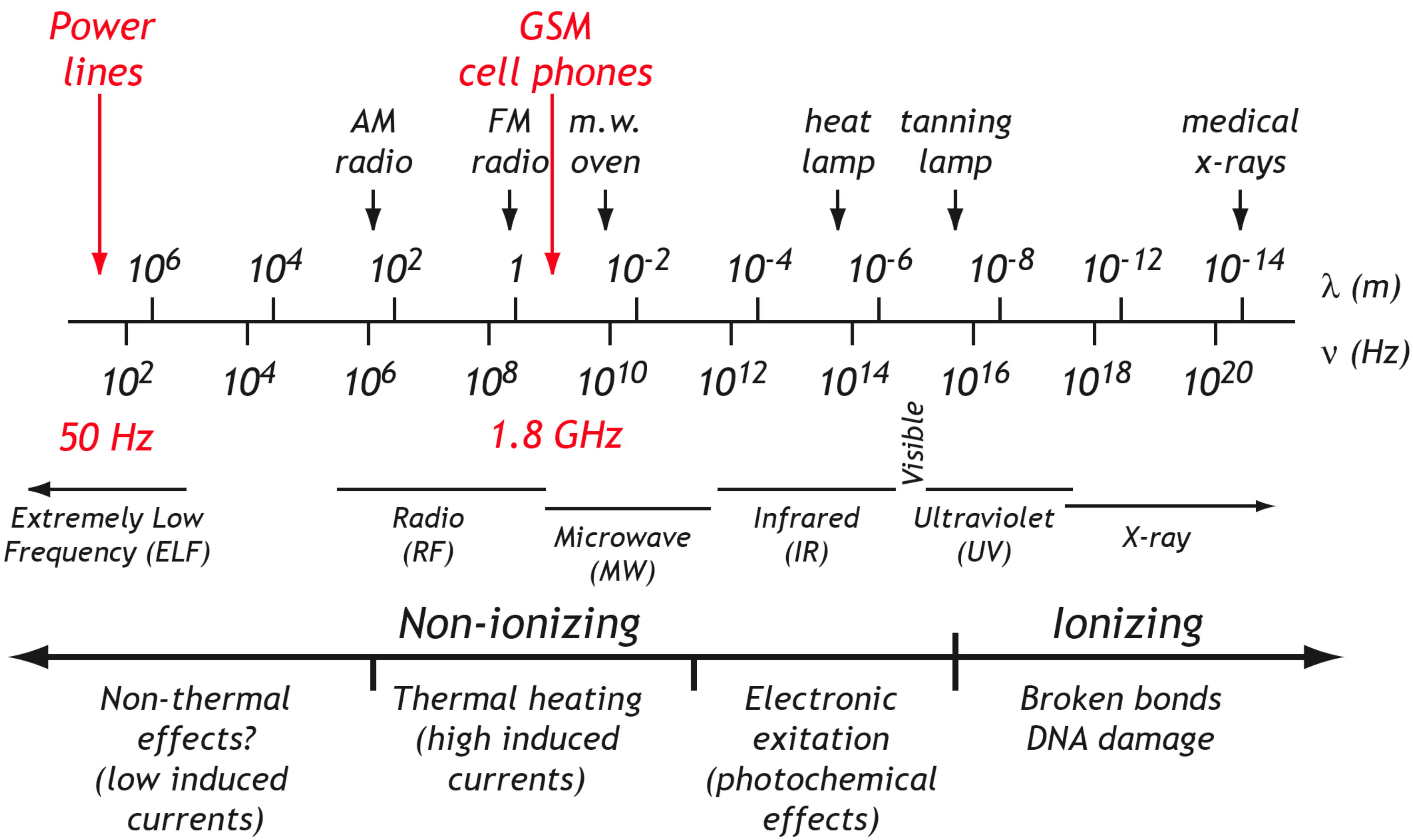
2005

Outline

- *GSM signal*
- *e.m. waves*
- *resonant cavities*
- *ETHZ apparatus*
- *SAR analysis*

e.m. spectrum


Power lines
GSM cell phones
AM radio
FM radio
m.w. oven
heat lamp
tanning lamp
medical x-rays
10^6 10^4 10^2 1 10^-2 10^-4 10^-6 10^-8 10^-12 10^-14
λ (m)
ν (Hz)
10^2 10^4 10^6 10^8 10^10 10^12 10^14 10^16 10^18 10^20
50 Hz
1.8 GHz
Visible
Extremely Low Frequency (ELF)
Radio (RF)
Microwave (MW)
Infrared (IR)
Ultraviolet (UV)
X-ray
Non-ionizing
Ionizing
Non-thermal effects? (low induced currents)
Thermal heating (high induced currents)
Electronic exitation (photochemical effects)
Broken bonds DNA damage

High frequency irradiation

High frequency e.m. waves hardly penetrate inside the body, largely because of the water content of the tissues:

$$I=I_0e^{-d/L},\ L<\lambda/10$$

frequency	λ (m)	L (m)
50 Hz	6000000	600000
1 kHz	300000	30000
1 MHz	300	30
1 GHz	0,3	0,03

Specific Absorption Rate (SAR)

The energy absorbed by the body is normalized to weight and time, and measured as SAR (Specific Absorption Rate), in units of:

$$\left[\frac{\mathrm{W}}{\mathrm{kg}}\right] = \left[\frac{\mathrm{J}}{\mathrm{kg\ s}}\right] = \left[\frac{\mathrm{Energy}}{\mathrm{kg\ s}}\right]$$

High frequency irradiation: requirements

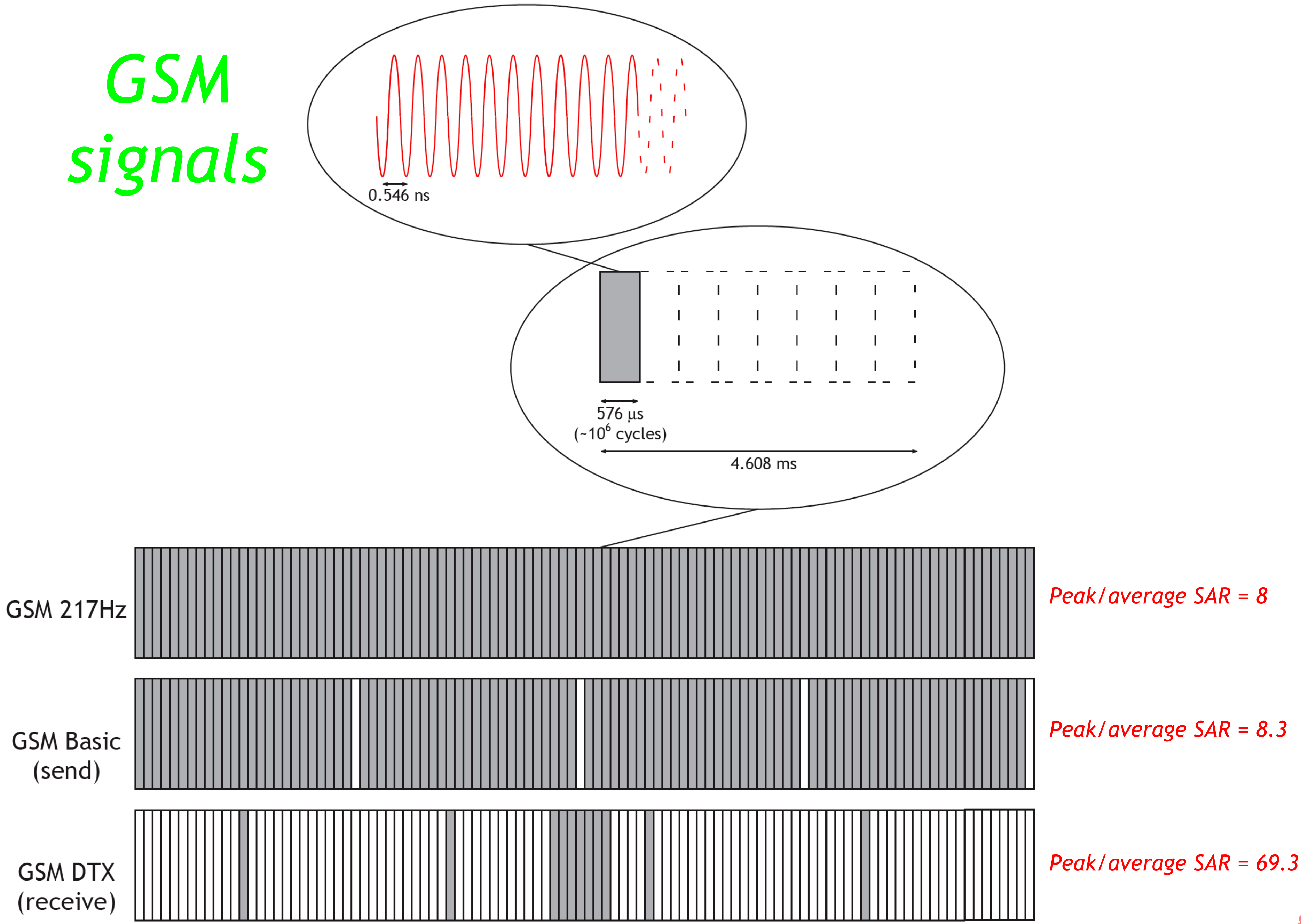
- *GSM signal (i.e. flexible signal)*
- *Fit into commercial incubator*
- *Standard Petri dishes*
- *Monolayer cells (in suspension if with limited water content)*
- *Temperature rise negligible at average SAR=2W/kg*
- *No temperature hot spots*
- *Peak SAR>50 W/kg/W_{input} (note: 2 W/kg average = 150 W/kg peak in DTX mode)*
- *SAR nonuniformity < 30%*
- *SAR uncertainty < SAR nonuniformity*
- *Isolation between exposure and sham < 30dB*
- *Same exposure and sham conditions with continuous monitoring*
- *Self-detecting malfunctioning*
- *Stable power (feedback regulation of the output power of the RF generator)*
- …

resonant cavity

GSM transmission - 1800 MHz band

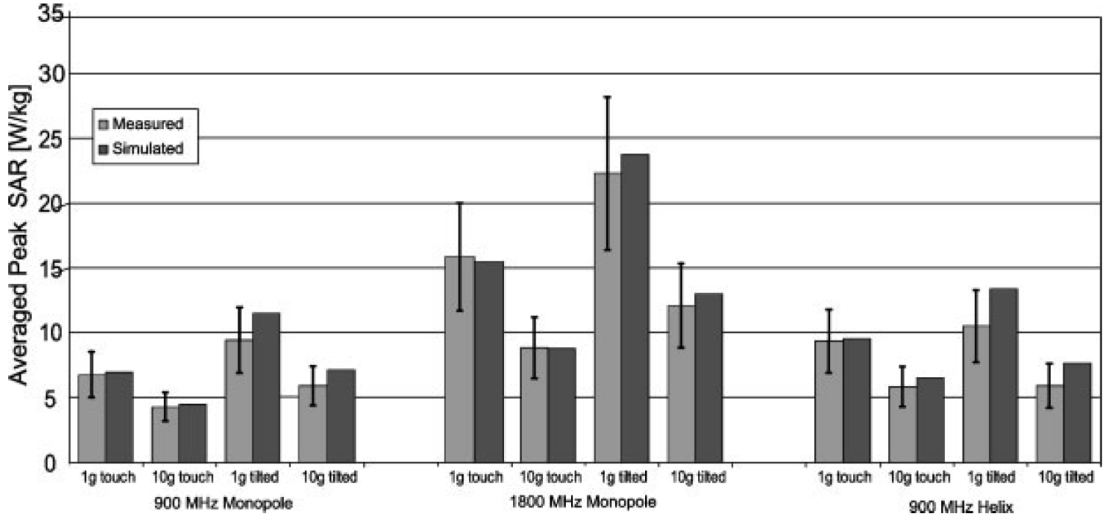
- *bandwidth: 75 MHz*
- *number of 200 kHz channels: 374*
- *number of phones which can use the same channel: 8 (with Time Division Multiple Access - TMDA)*
- *pulse duration: 4.608 ms*
- *active time in one pulse: 576 μs (pulse modulation: 217 Hz)*
- *omitted pulses: 1 every 26 (additional pulse modulation: 8.34 Hz)*
- *power emission is adjusted to the strength of the signal: Adaptive Power Control (APC)*
- *power is switched off if not speaking: Discontinuous Transmission (DTX)*

GSM signals


0.546 ns
576 μs
(~10^6 cycles)
4.608 ms
GSM 217Hz
GSM Basic
(send)
GSM DTX
(receive)
Peak/average SAR = 8
Peak/average SAR = 8.3
Peak/average SAR = 69.3

GSM handsets

- *maximum power allowed by law: 1 W*
- *fields at 2.2 cm from antenna: E=200 V/m, B=6 μT*
- *intensity at 2.2 cm from antenna: I=200 W/m^2 (1/4 of the Sun's radiation in a clear day)*
- *max SAR: 20-25 W/kg*



Kuster N., Bioelectromagnetics, 2005

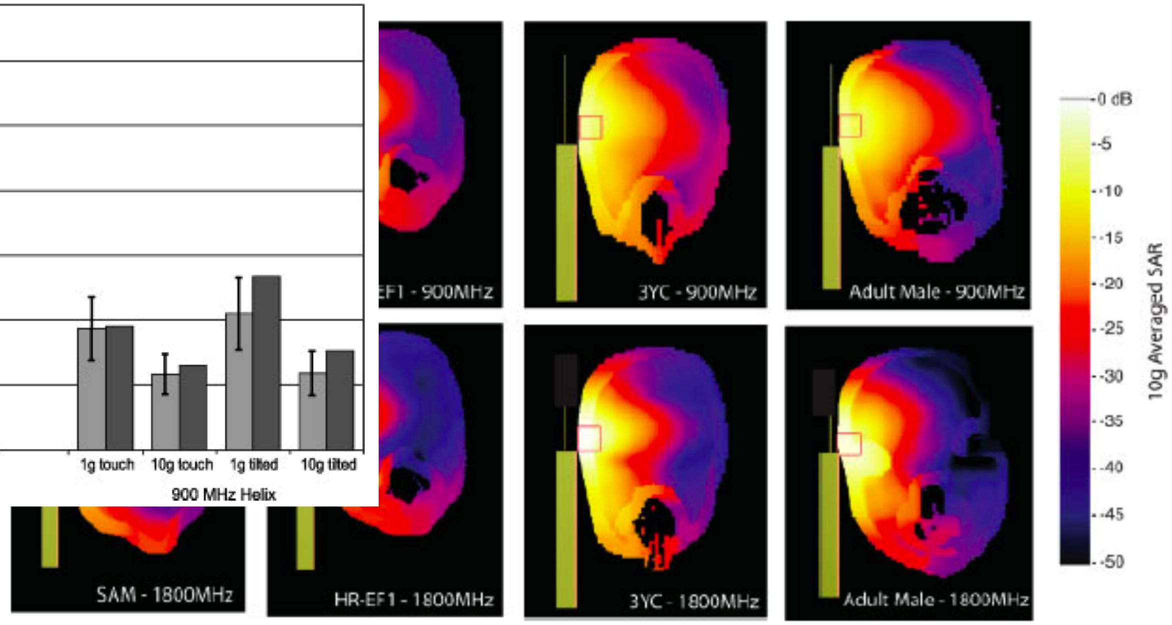


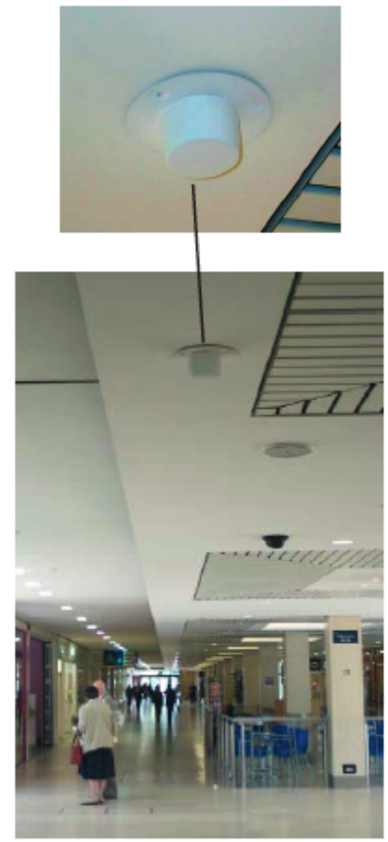
Fig. 7. Ten-gram average SAR distributions for SAM and the three anatomical phantoms in the "tilted" position for the GMP with monopole antenna. 0 dB corresponds to 15 W/kg normalized to 1W antenna output power. The square indicates the location of the averaged SAR maximum.

GSM antennas

- *standard cell typical power: 3 kW (directional, 120° sector)*
- *beam vertical aperture: 6°*
- *maximum intensity at 50 m from antenna: I=100 mW/m² (1000 times smaller than from handset)*

standard cell

microcell



picocell

Waveguide

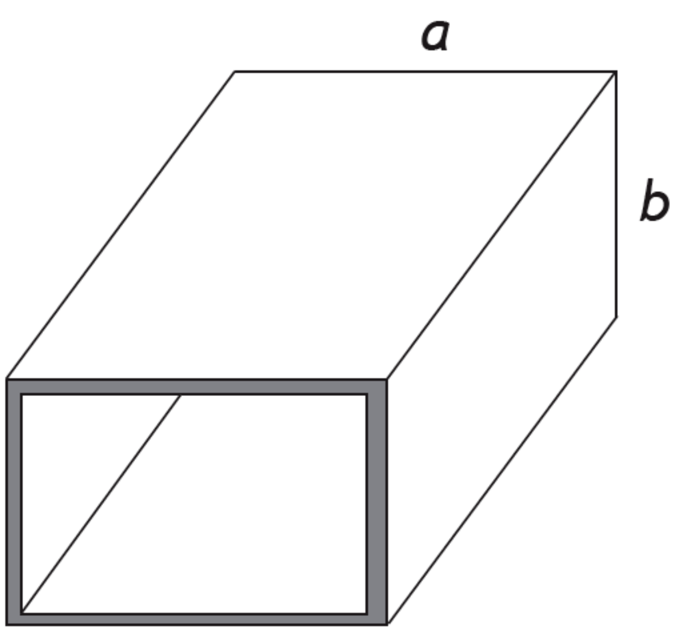
A wave guide is an empty tube with conductive walls into which an electromagnetic wave propagates.

It is used when a high frequency signal (>1GHz) has to be transmitted for long distances without power losses.

A waveguide can be imagined as an extension of the coaxial cable (e.g., TV cable).

Waveguide

(infinite length box with conductive walls)



Consequences of conductive walls:

the electric field can only be perpendicular to the walls

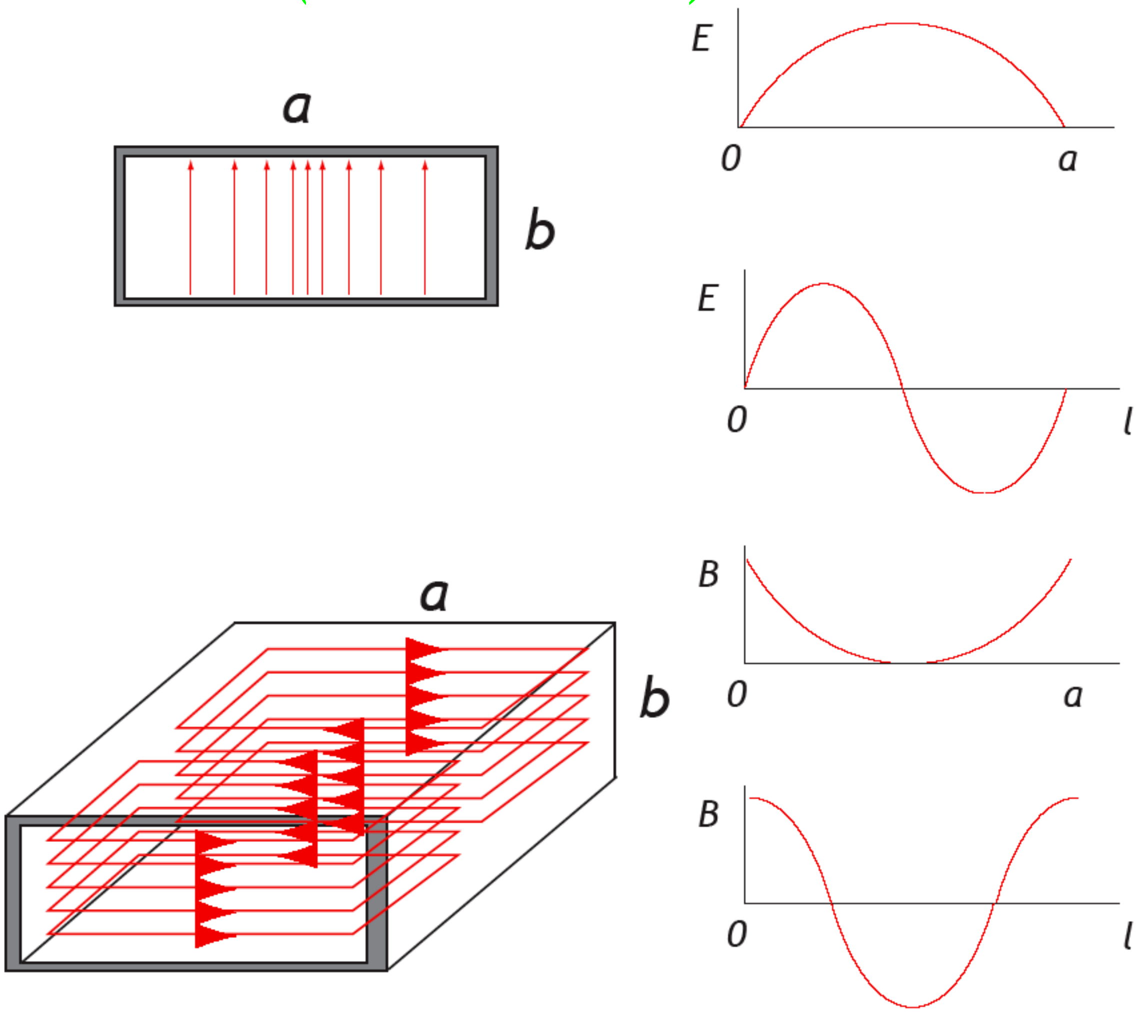
the magnetic field can only form close loops parallel to the walls and perpendicular to the electric field

an e.m. wave travelling inside the cavity can be a superposition of several waves with different wavelength, phase and amplitude

the e.m. wave travelling inside the cavity is “reflected” at the walls

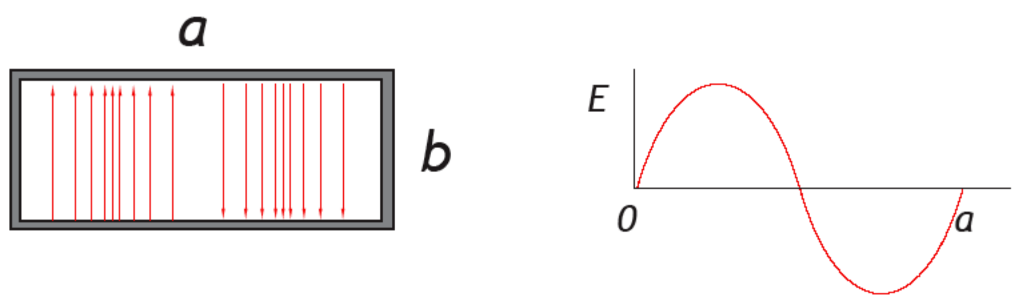
Electric and Magnetic fields inside the waveguide

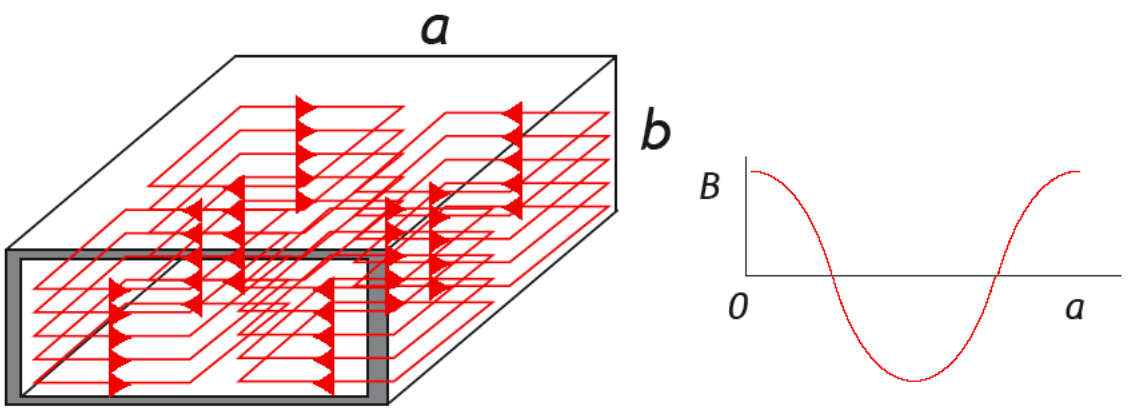
(dominant mode)



Electric and Magnetic fields inside the waveguide

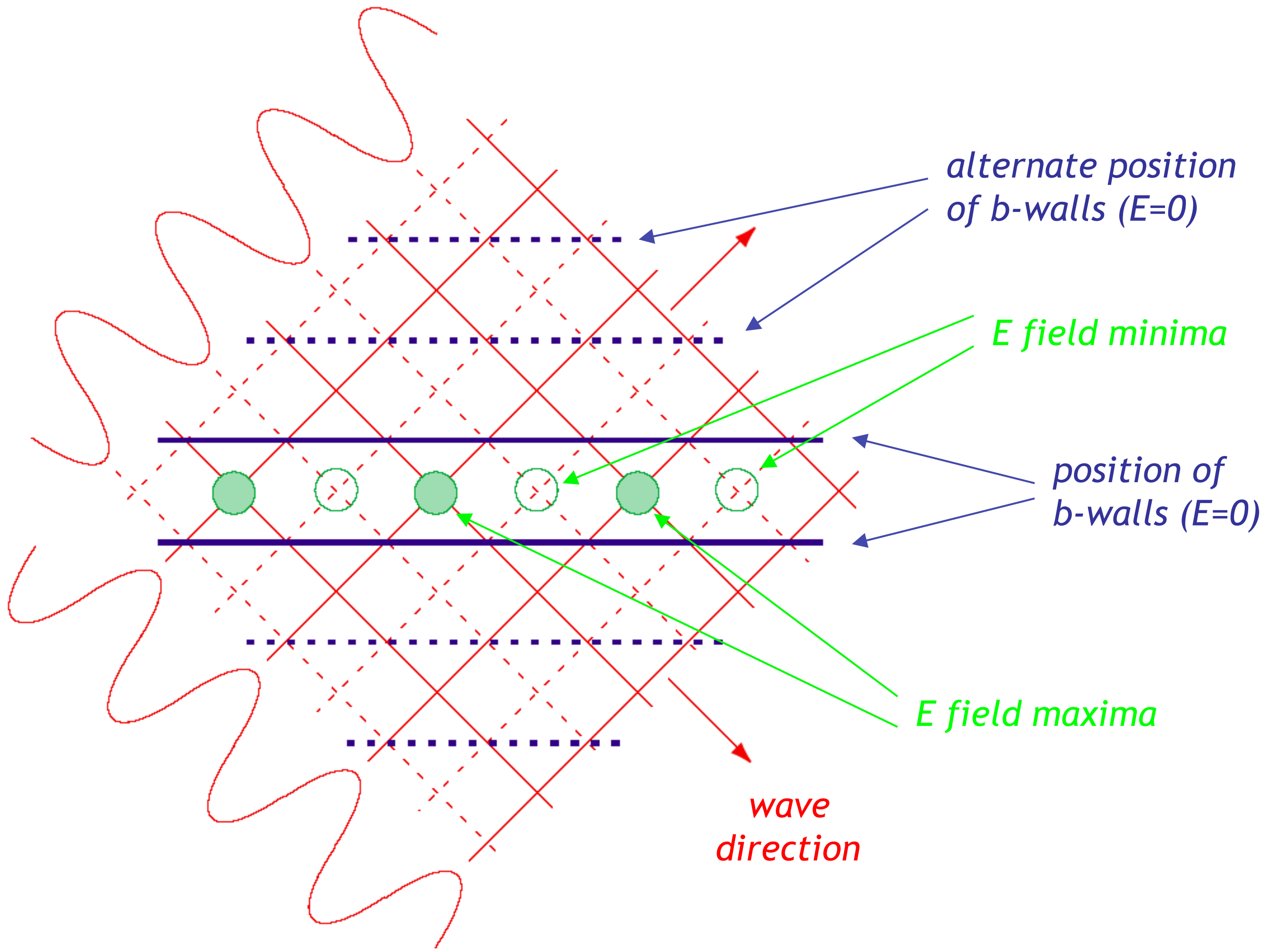
(other modes)





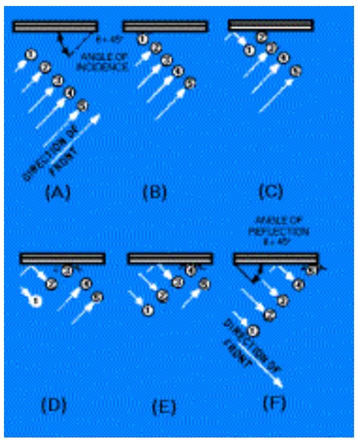
How to get E=0 at b-walls

two waves with the same frequency moving at an angle from each other

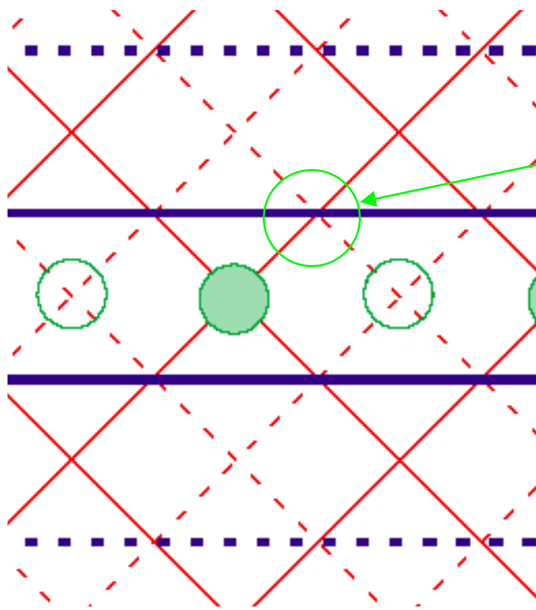


Reflection on the walls

Reflection:

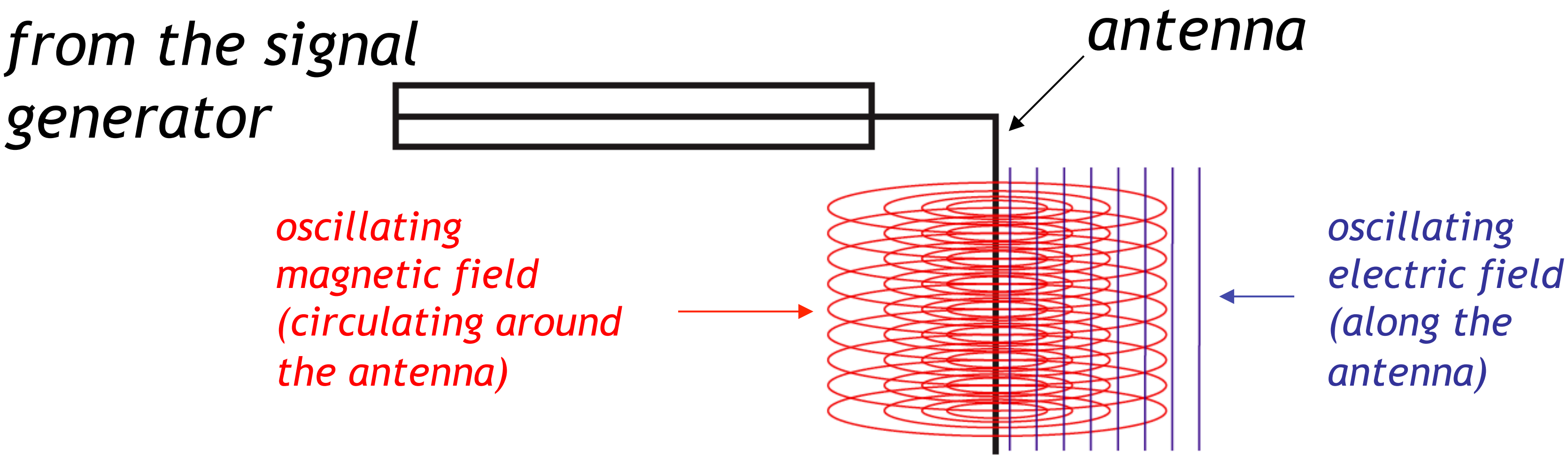


A reflection changes the phase of the wave by 180°

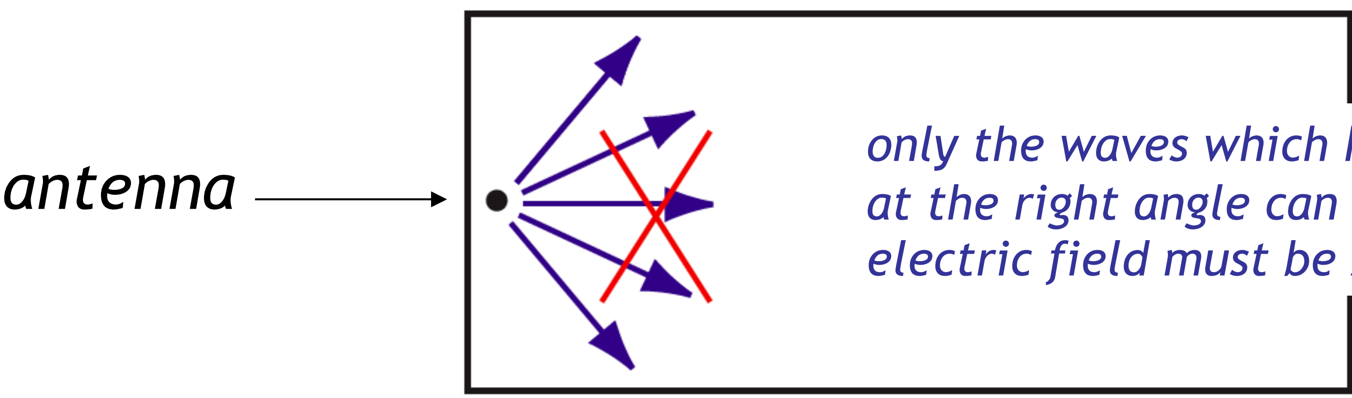


The incident wave has the E field at its minium; the reflected wave at its maximum

How the resonant wave is induced in the waveguide



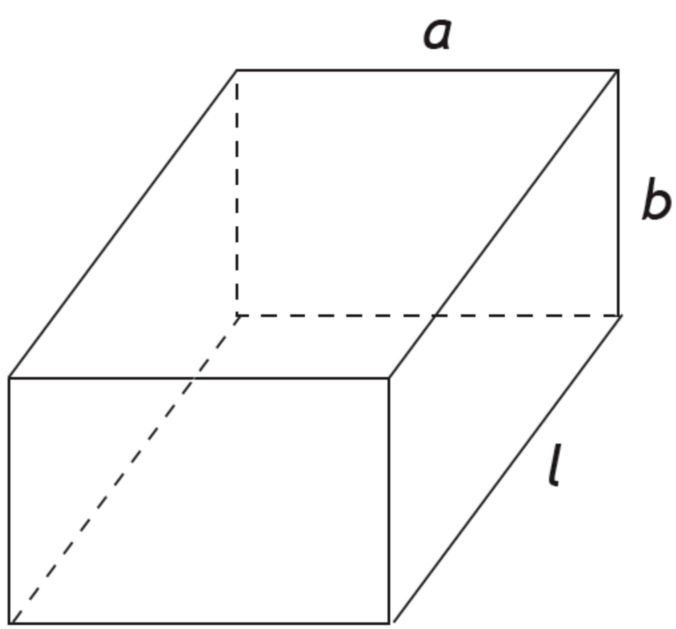
both the magnetic and the electric field propagate in space



only the waves which hit the walls at the right angle can survive because the electric field must be zero at the walls

Resonant cavity

(finite length box with conductive walls)

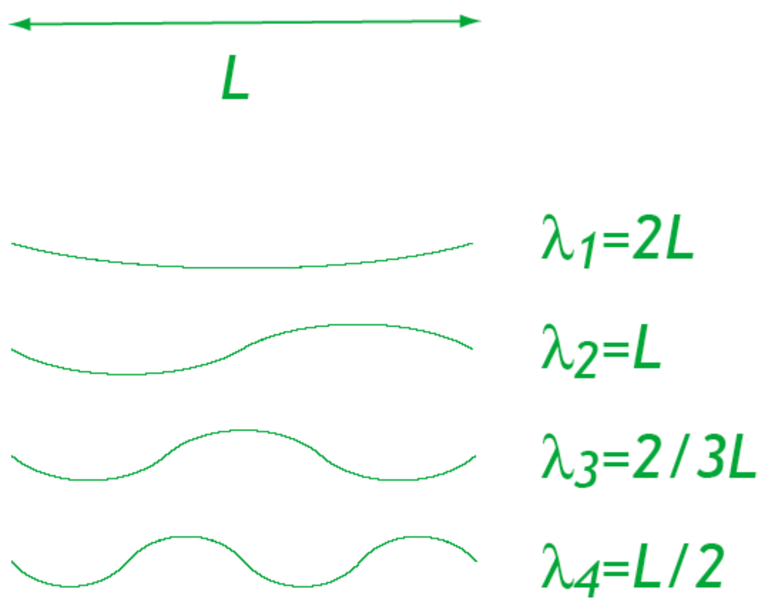


effect of conductive walls:

same as waveguide

(but two more boundary conditions)

Rope fixed on both ends



$$\lambda = \frac{2L}{n}$$

$$k = \frac{2\pi}{\lambda} = \frac{n\pi}{L}$$

all waves (armonics) can be present at any time

a perturbation travelling along the rope is a superposition of all armonics with different phases and amplitudes

a perturbation travelling along the rope is "reflected" at the fixture

Resonant cavity: electric field configuration

$$\bar{E} = \bar{E}_0 cos(\omega t - \bar{k} \cdot \bar{r})$$

$$\boxed{k_1 = \frac{n_a \pi}{a}; k_2 = \frac{n_b \pi}{b}; k_3 = \frac{n_l \pi}{l}}$$

← *boundary conditions*

$$E_x = E_1 \cos(k_1 x) \sin(k_2 y) \sin(k_3 z) \cos(\omega t)$$
$$E_y = E_2 \sin(k_1 x) \cos(k_2 y) \sin(k_3 z) \cos(\omega t)$$
$$E_z = E_3 \sin(k_1 x) \sin(k_2 y) \cos(k_3 z) \cos(\omega t)$$

E.M. frequency

$$\nu = \frac{\omega}{2\pi} = \frac{kc}{2\pi} = \frac{c}{2\pi}\sqrt{\frac{n_a^2}{a^2} + \frac{n_b^2}{b^2} + \frac{n_l^2}{l^2}}$$

If the electric field is vertical (along b dimension):

$$n_b = 0$$

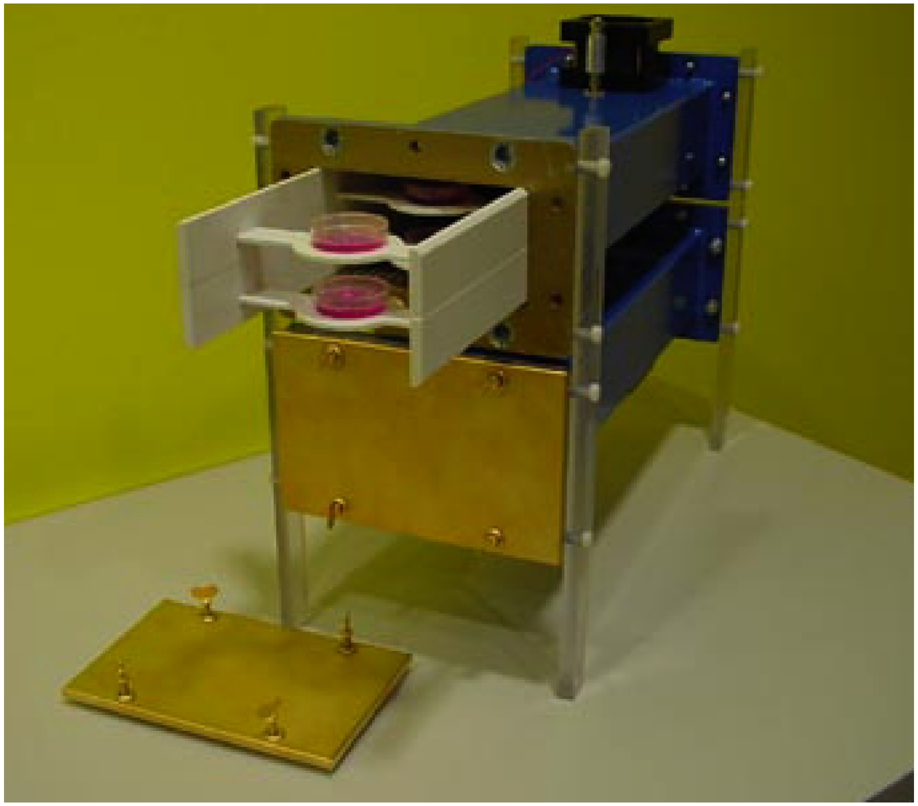
$$\nu = \frac{c}{2\pi}\sqrt{\frac{n_a^2}{a^2} + \frac{n_l^2}{l^2}}$$

$|E| = E_y =$
$E_2 \sin(k_1 x)\sin(k_3 z)\cos(\omega t)$

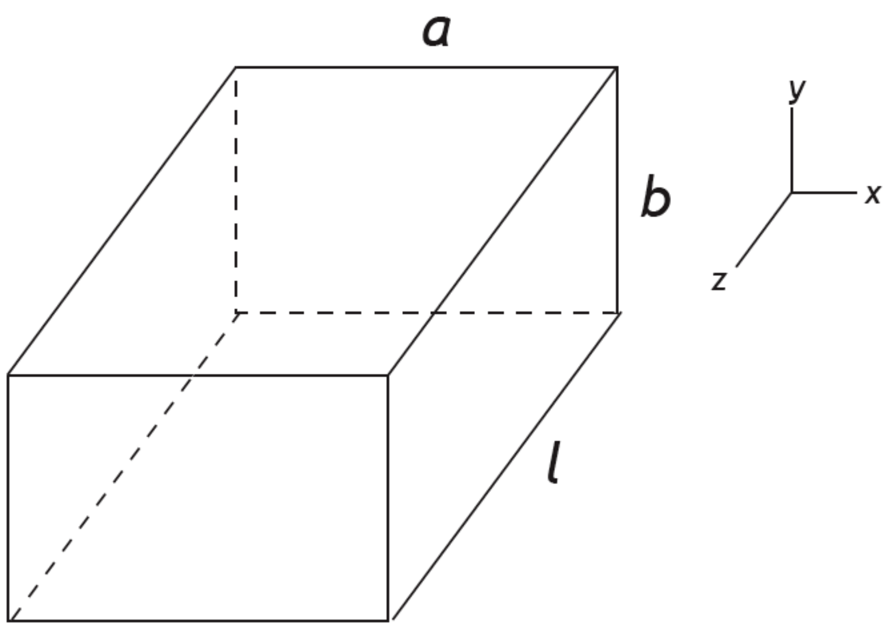
then, from : $\nabla \times \bar{E} = -\frac{\partial \bar{B}}{\partial t}$,
B can be derived :

$B_x = \sin(k_3 z)\cos(k_1 x)$
$B_z = -\cos(k_3 z)\sin(k_1 x)$

ETHZ Apparatus



ETHZ Apparatus

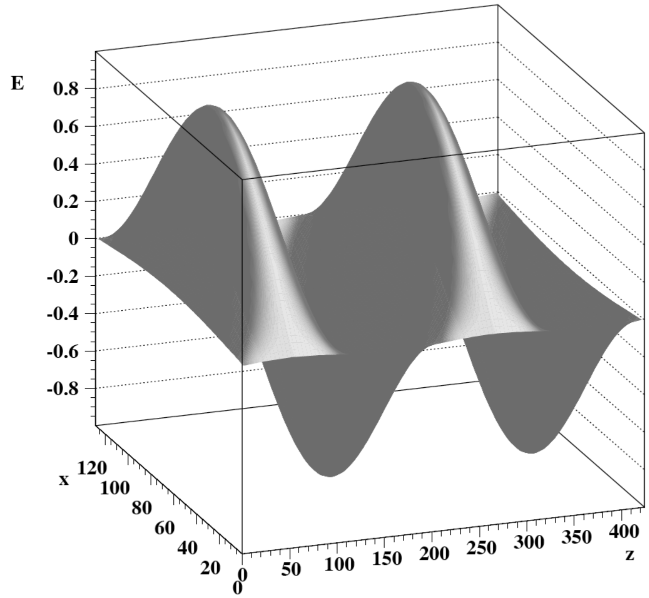


na	nb	nl	frequency (GHz)
1	0	1	1.209
2	0	1	2.340
3	0	1	3.488
1	0	2	1.355
2	0	2	2.418
3	0	2	3.541
1	0	3	1.568
2	0	3	2.544
3	0	3	3.628
1	0	4	1.824
2	0	4	2.710
3	0	4	3.746
1	0	5	2.109
2	0	5	2.909
3	0	5	3.892
1	0	6	2.412
2	0	6	3.135
3	0	6	4.064

a=129.6 mm
b=64.8 mm
l=425 mm

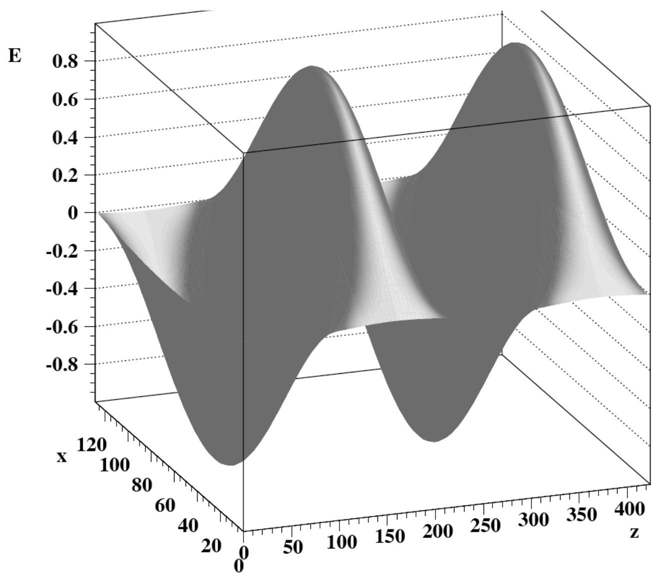
Note: the resonant frequency is slightly reduced when the Petri dishes are inserted, due to the high conductivity of the medium.

Electric field

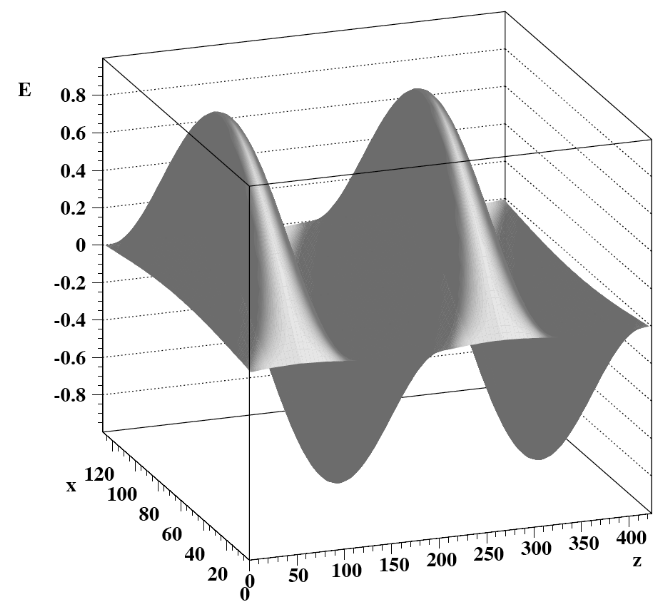


t=0

The E field oscillates with time with frequency ν, inverting the direction every half a cycle.



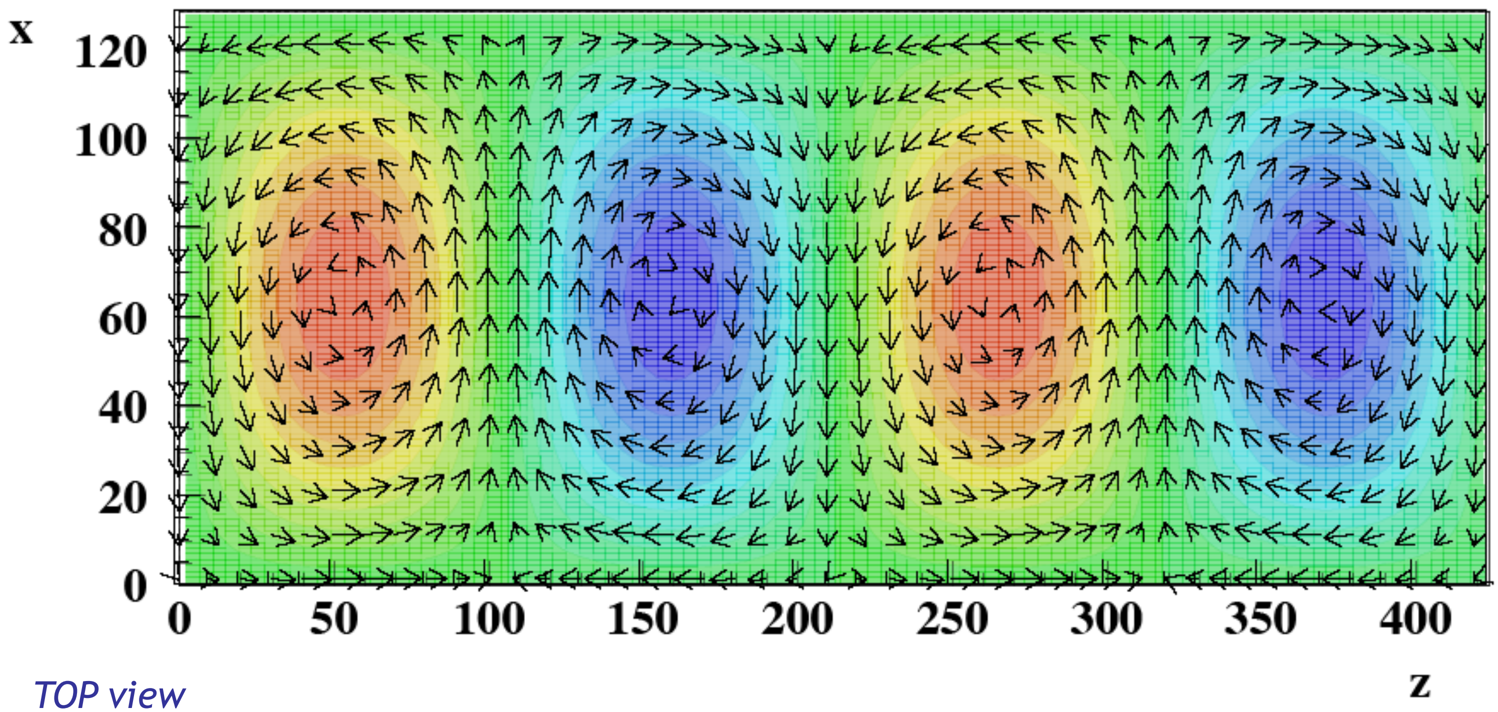
t=T/2=
1/2ν



t=T=
1/ν

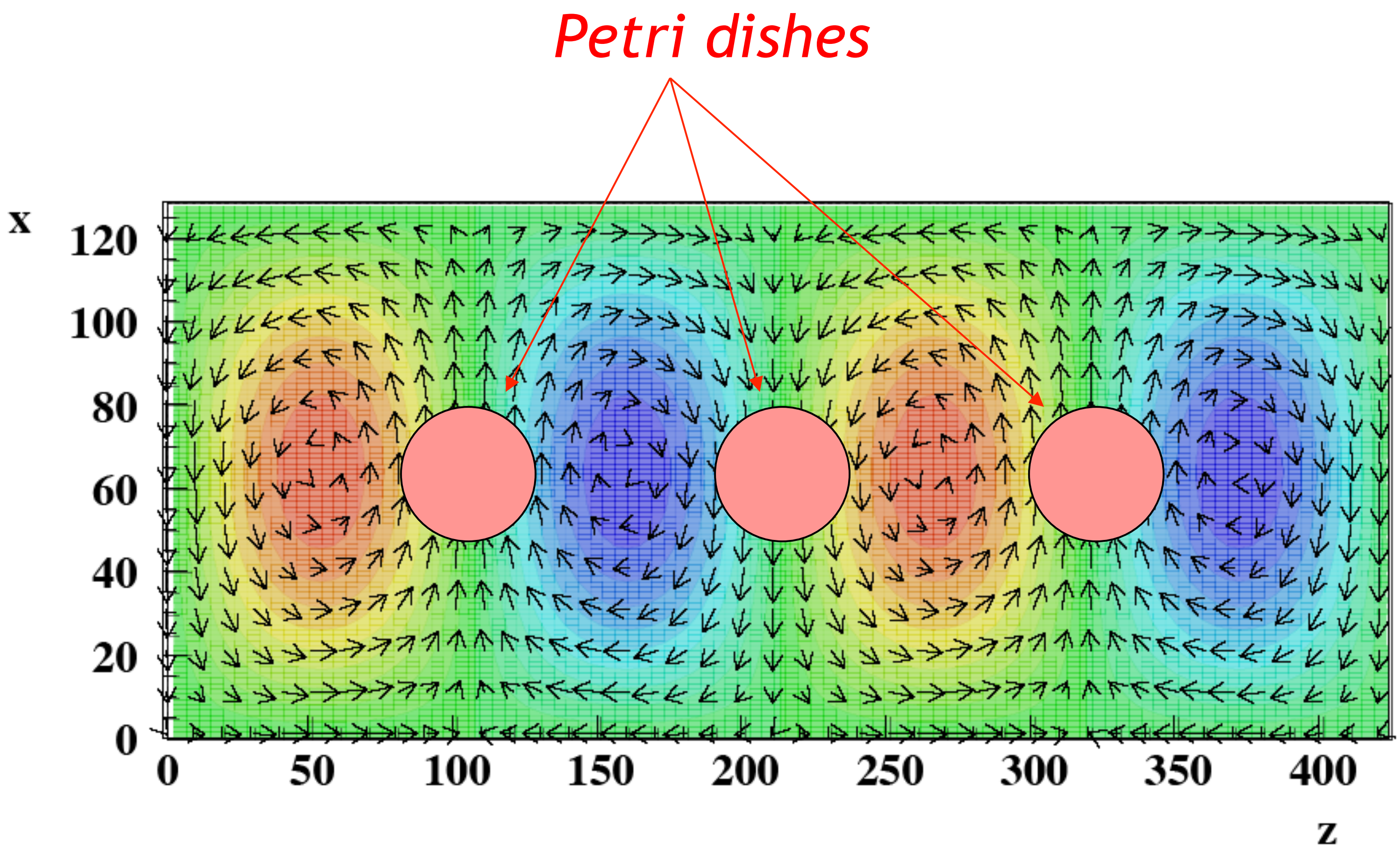
Magnetic field

Also the B field oscillates with time with frequency ν, inverting the direction every half a cycle.



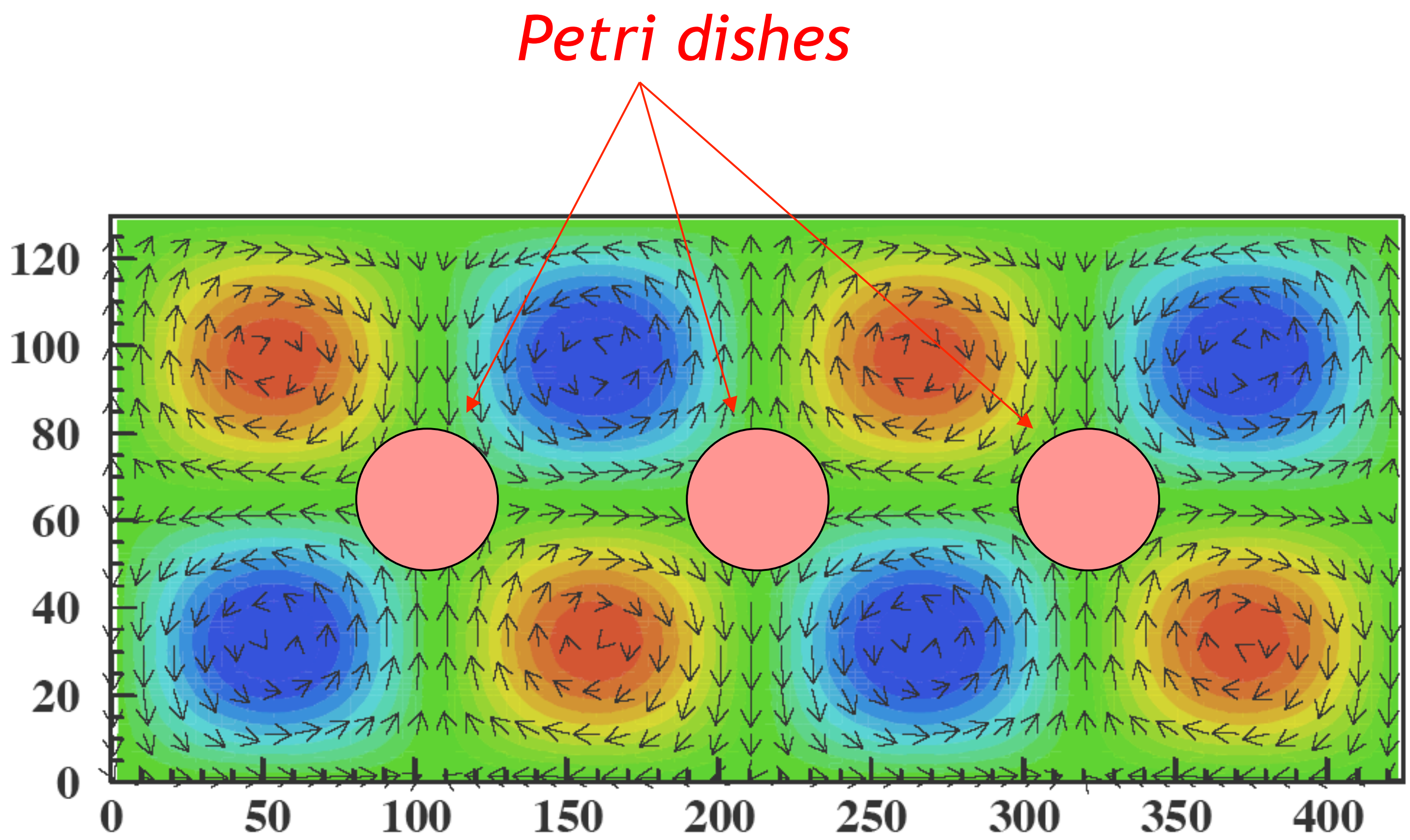
TOP view
E-field: red and blue spots
B-field: arrows

Field on Petri dishes

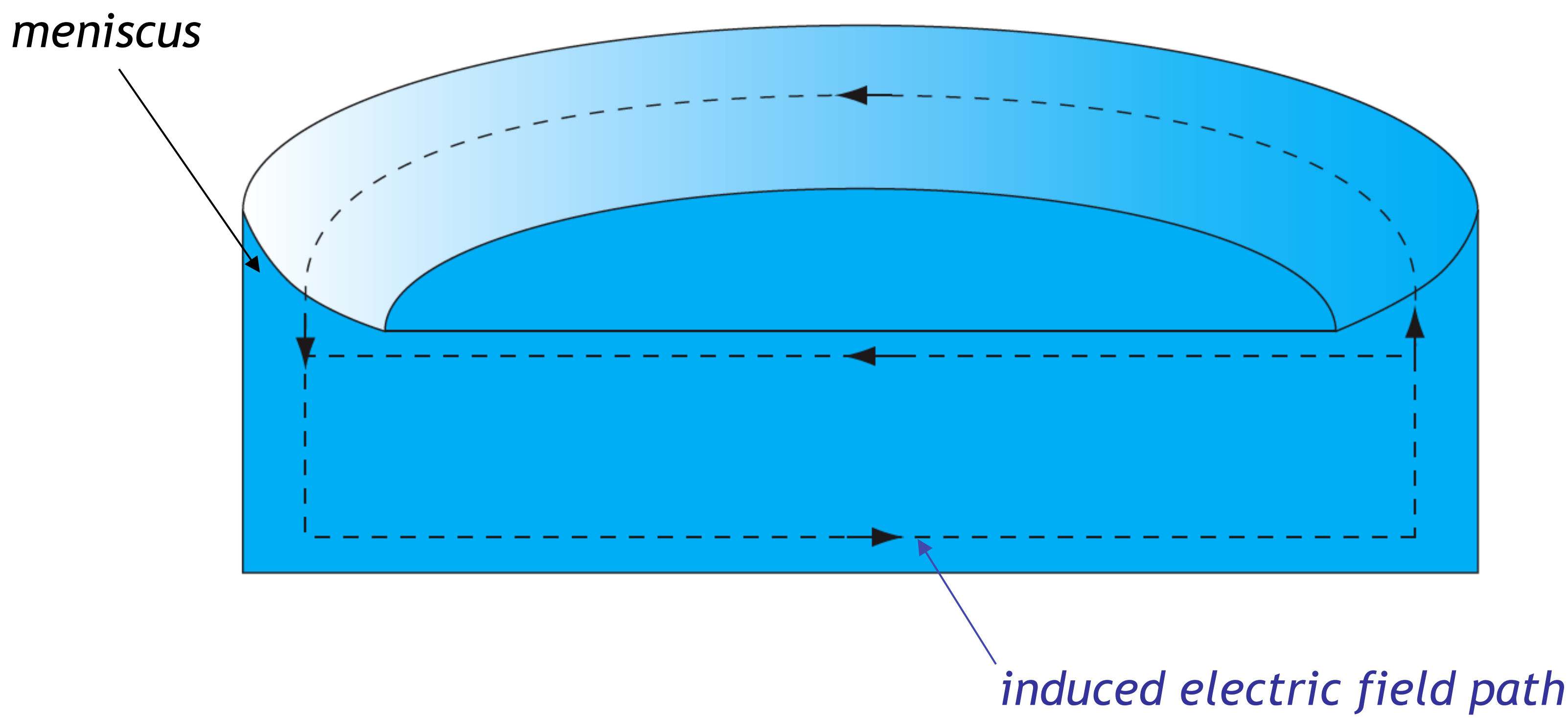


Petri dishes are positioned where the magnetic field is larger (E is smaller). The magnetic field is tangent to the liquid surface.

Field on Petri dishes if n_a=2 (resonance al 2.71 GHz)

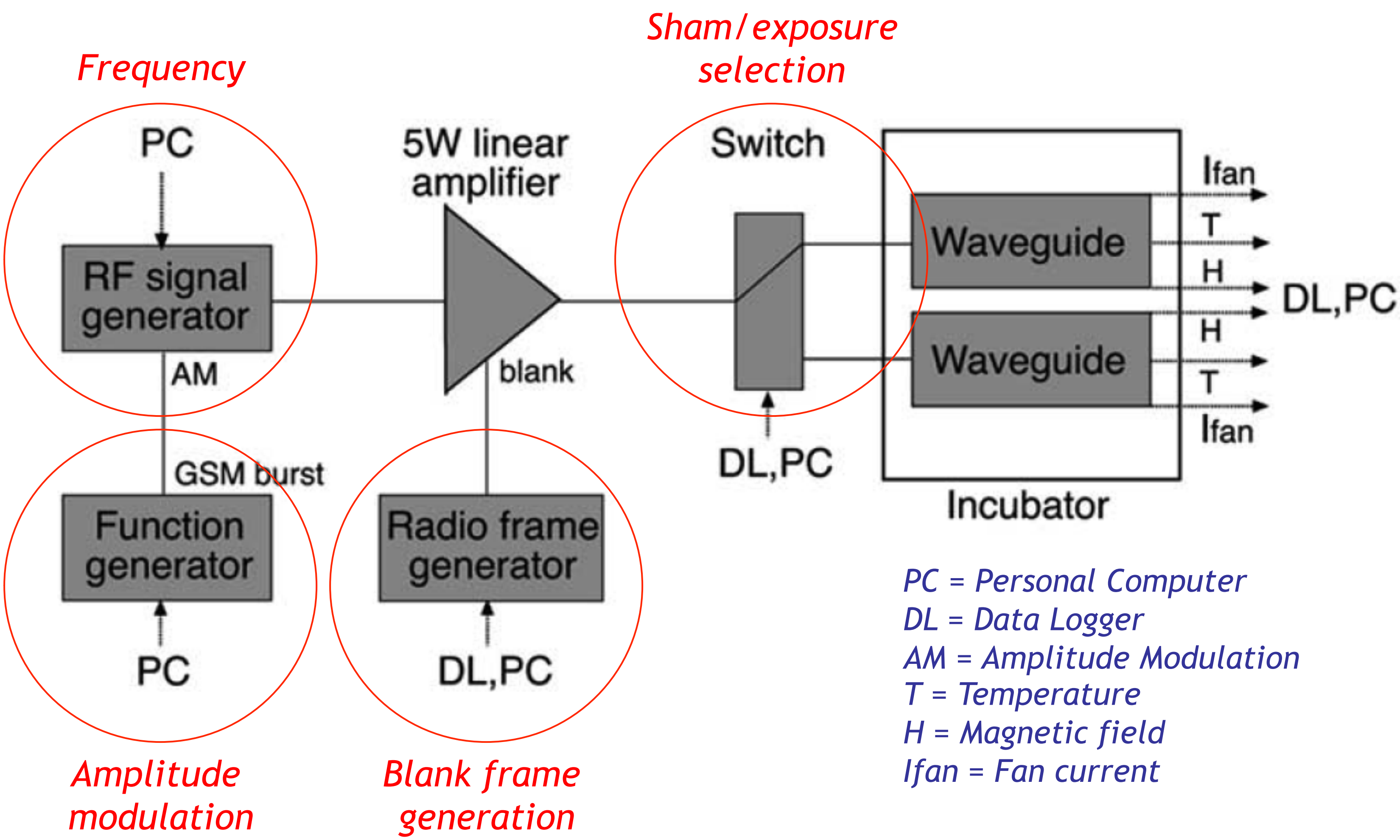


Induced electric field



Due to the large conductivity of the medium, a large oscillating electric field, circulating around the magnetic field, is induced in the liquid inside the Petri dish. The meniscus contributes with additional closed paths, further increasing the electric field.

Signal generation



PC = Personal Computer
DL = Data Logger
AM = Amplitude Modulation
T = Temperature
H = Magnetic field
Ifan = Fan current

SAR calculation

$$\text{SAR} = \left[\frac{\text{W}}{\text{kg}}\right] = \left[\frac{\text{J}}{\text{kg s}}\right] = \left[\frac{\text{Energy}}{\text{kg s}}\right]$$

Notes:

for V = 3 ml (h = 3.42 mm), the weight of the medium is: $\rho V = \rho\pi r^2 h \approx 30$ *g*
in order to get a SAR of 2 W/kg in 1 hour, an energy of about 22 J has to be delivered
this implies an increase in temperature of $\Delta T = \text{Energy}/mc_V \approx 1.7\ ^\circ C$ *and therefore the need for ventilation*

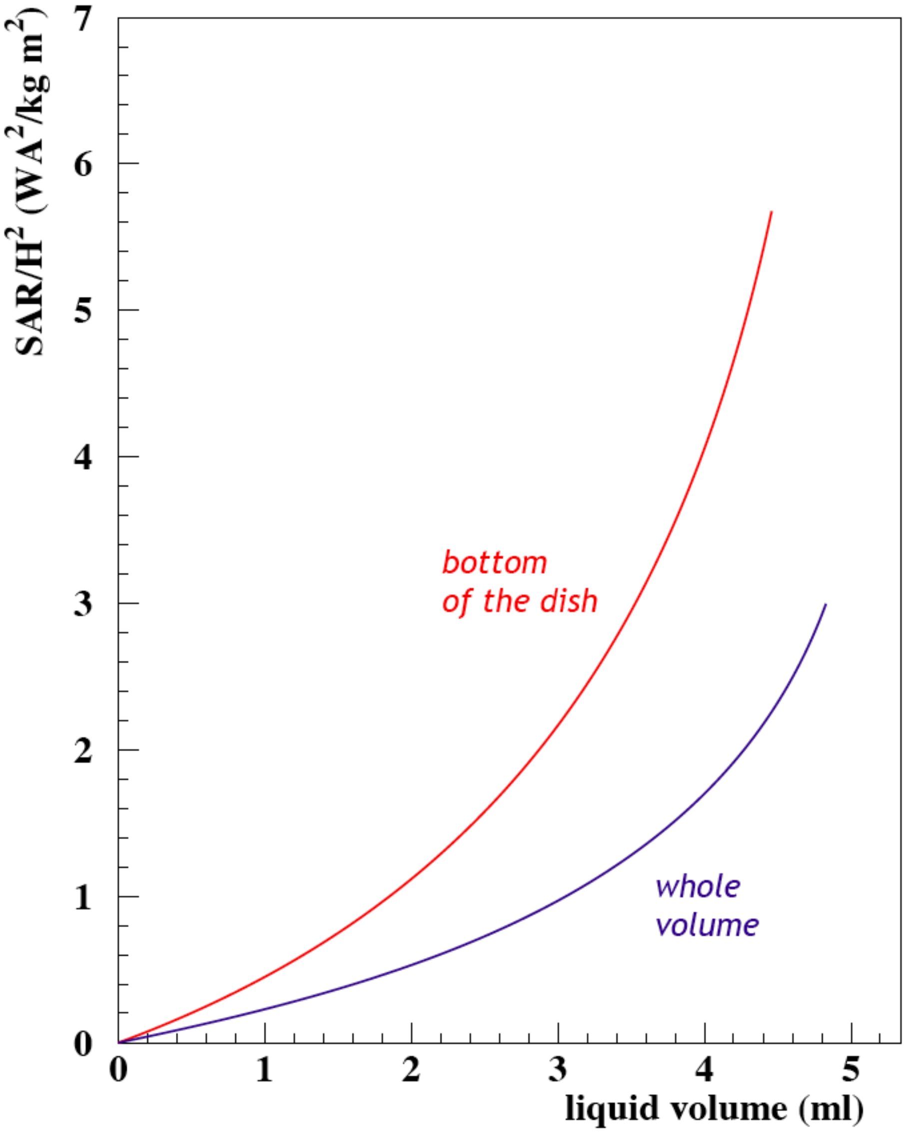
the fields can be derived from the Poynting's vector (energy/m^2s):
$E \approx 45$ *V/m, B=1.5 μT,* $H = B/\mu_0 \approx 1.2$ *A/m*

SAR depends on:

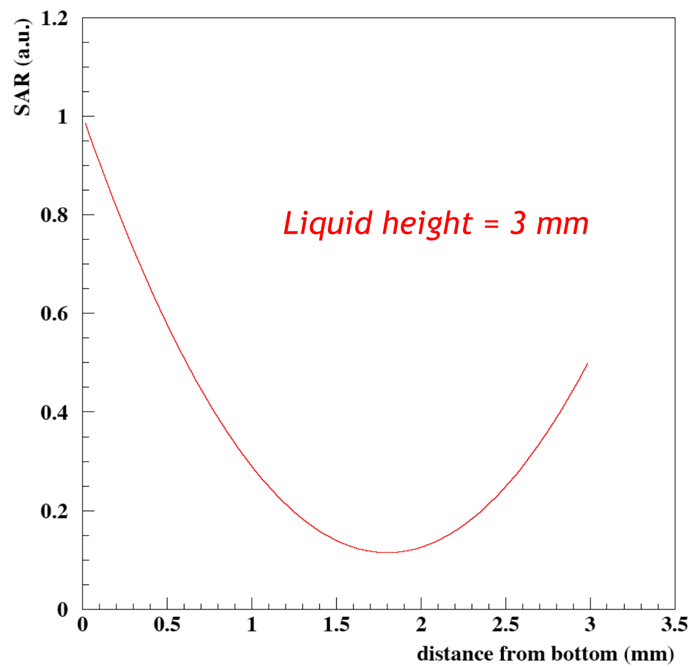
- *value of the magnetic field*
- *quantity of medium*
- *position of the cells inside the medium*
- *conductivity of the medium*
- *height of the meniscus*

Most results from J. Schuderer et al., IEEE Transactions on Microwave Theory and Techniques, 2004, 52:8:2057-2066.

Magnetic field, medium quantity and position of the cells



SAR depends quadratically on the magnetic field (amplitude of the wave) and nearly quadratically on the volume of the medium.
SAR at the bottom of the dish is largest.



Conductivity

SAR depends linearly on the conductivity of the medium.

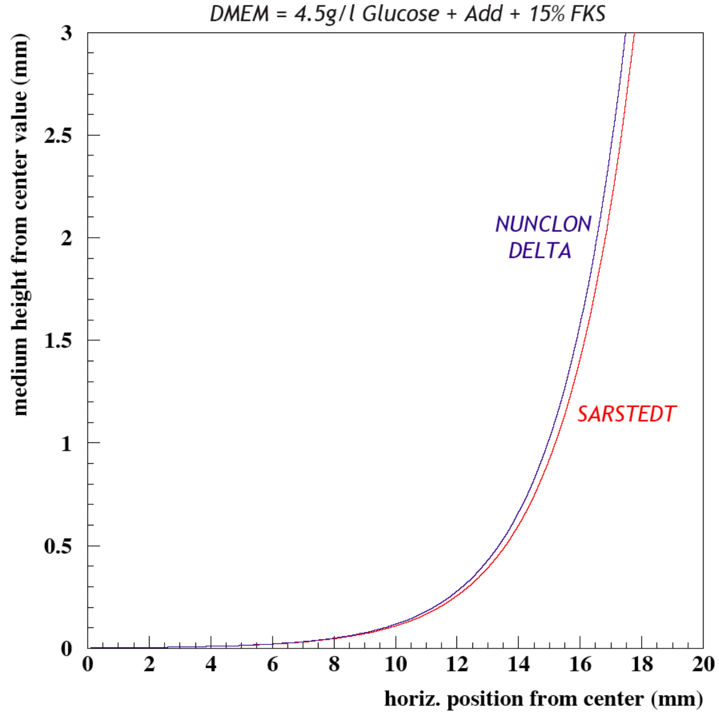
$$SAR \approx \frac{\sigma}{\rho} |E_{\text{ind}}|^2$$

$$\begin{aligned} \sigma &= \text{conductivity} \\ \rho &= \text{density} \\ E_{\text{ind}} &= \text{induced electric field} \end{aligned}$$

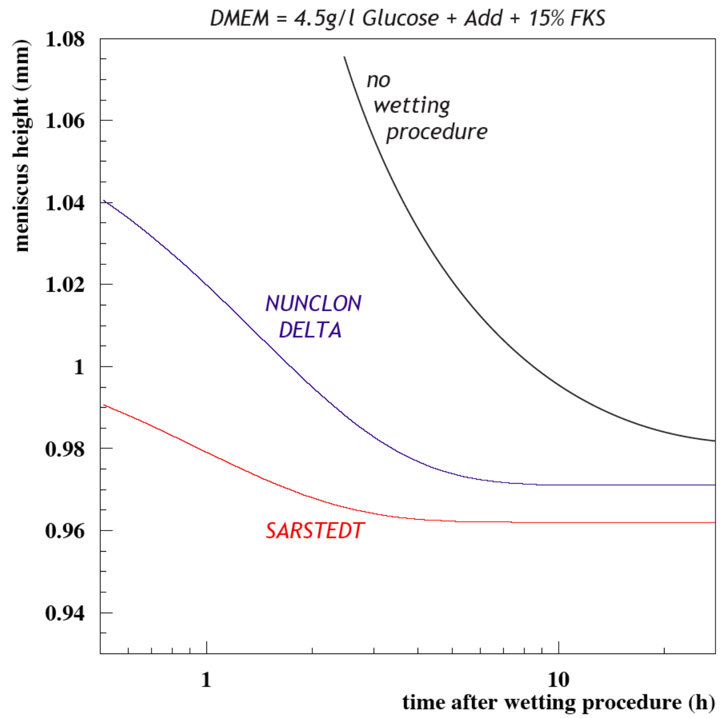
The conductivity of different liquids may differ by 10-15%.
σ (Bologna-DMEM) = 2.2 S/m

Meniscus in different Petri dishes

meniscus height

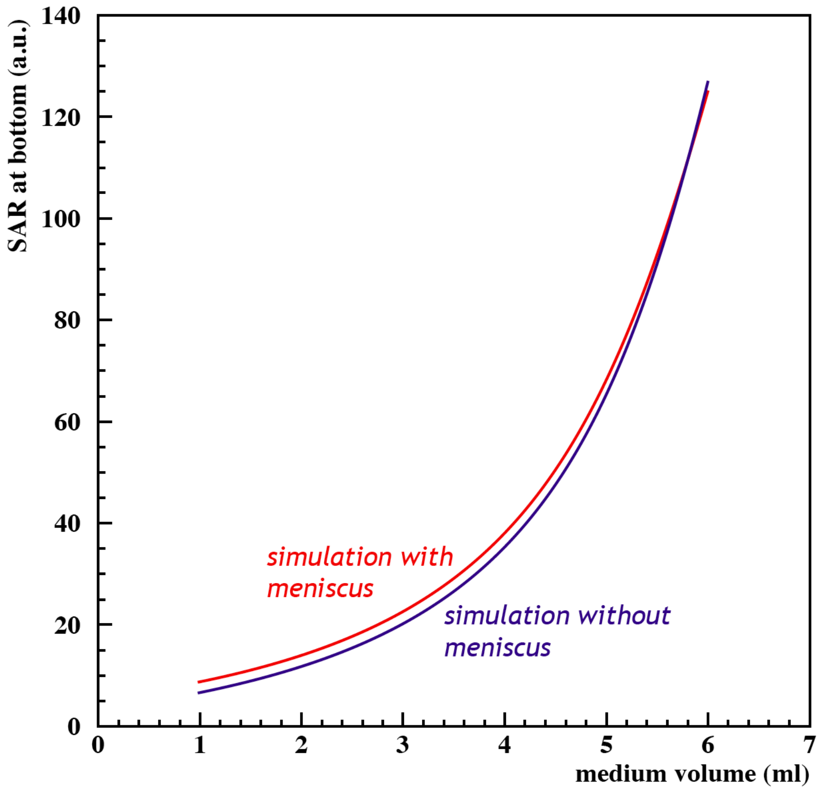


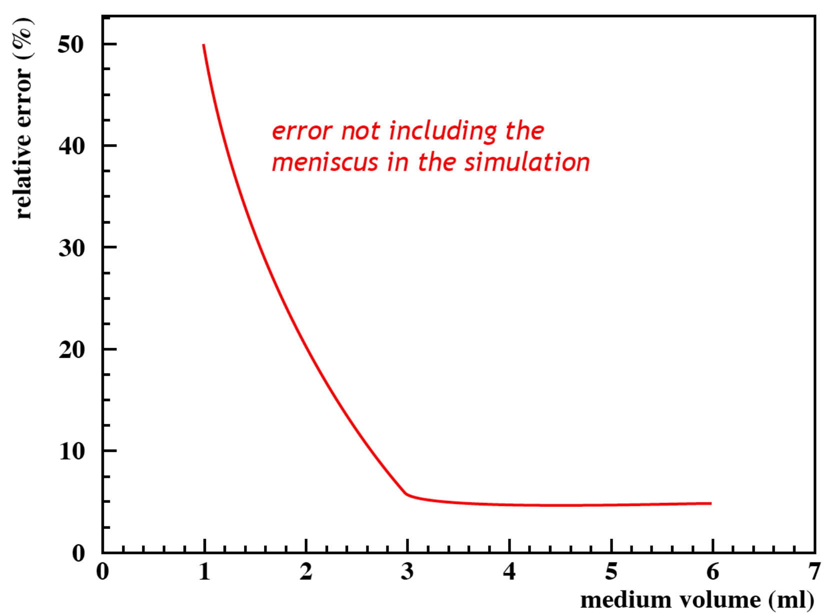
wetting procedure:
fill with 1 ml more
than take it away



Meniscus relevance

the relevance of the meniscus increases for small volumes





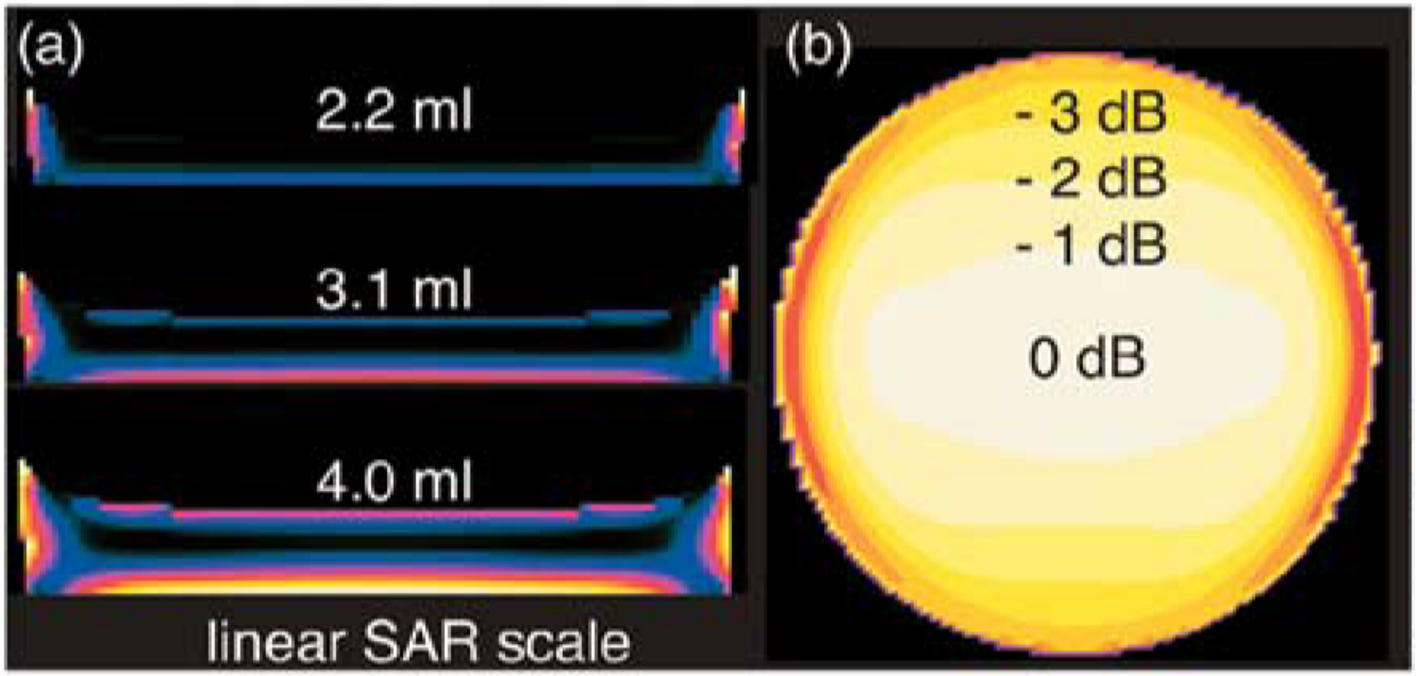
Uncertainty of SAR assessment (experimental)

Fit for extrapolation to monolayer	2.8%
Fit for varying medium volume (2.2 - 4.9 mL)	1.9%
Height of cell monolayer (z $\leq$ 0.1 mm)	4.8%
Numerical discretization (0.1 mm^3 reference)	8.2%
Determination of medium volume ($\pm 5 \mu L$)	0.3%
Determination of dielectric parameters	11%
Calibration of dosimetric E-field probe	7.6%
Probe positioning in Petri dish	1.6%
Calibration of monopole sensor for incident fields	11%
Combined relative uncertainty (RSS)	**20%**

SAR variability

Frequency dependency of loop coupler	4.5%
Determination of medium volume ($\pm 5\mu L$)	0.3%
Dish holder misplacement in waveguide ($\pm 2mm$)	0.7%
Assessment of incident fields	2.2%
Power drift	0.5%
Combined relative variability (RSS)	**5.1%**

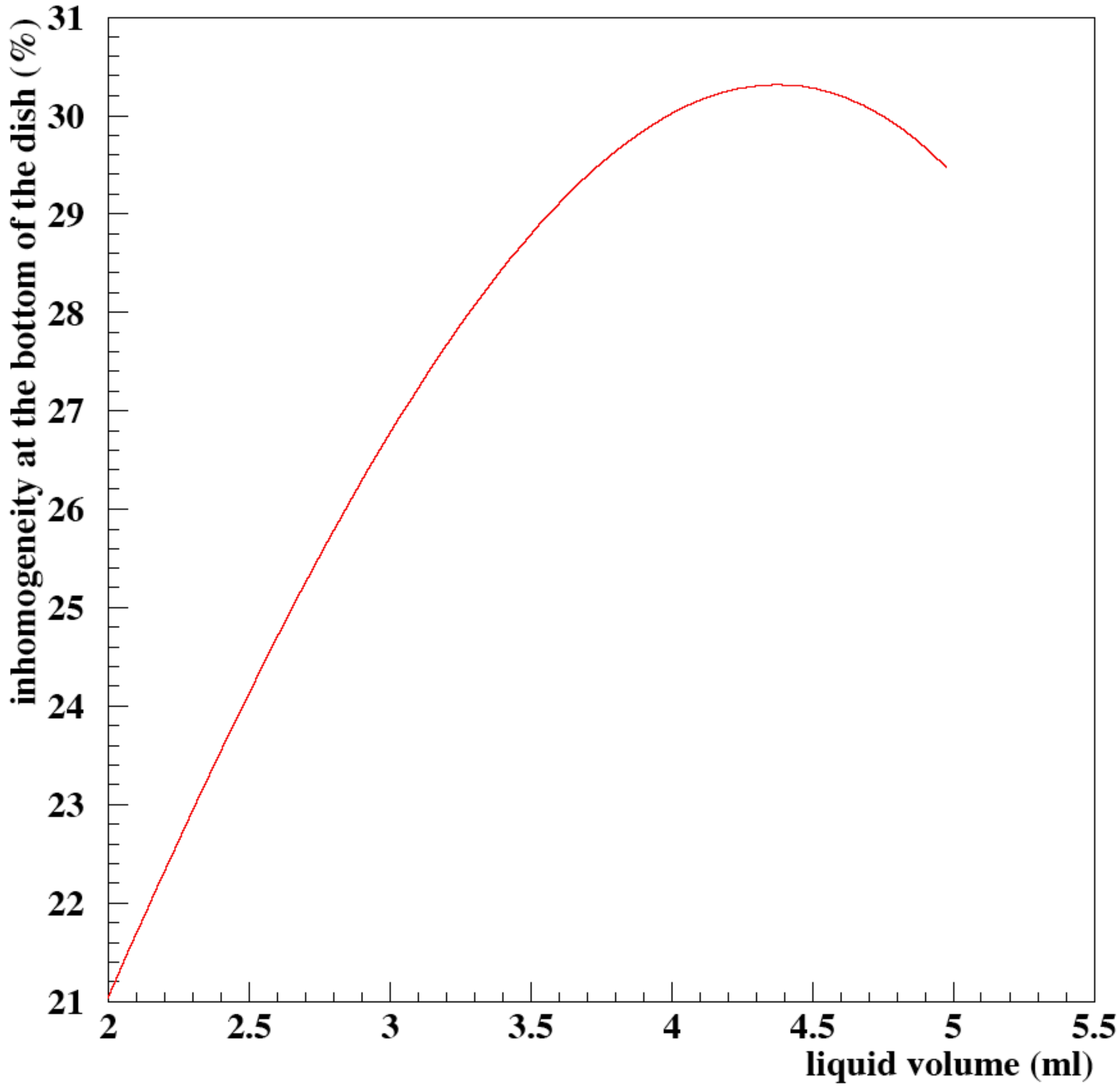
SAR inhomogeneity: simulation results



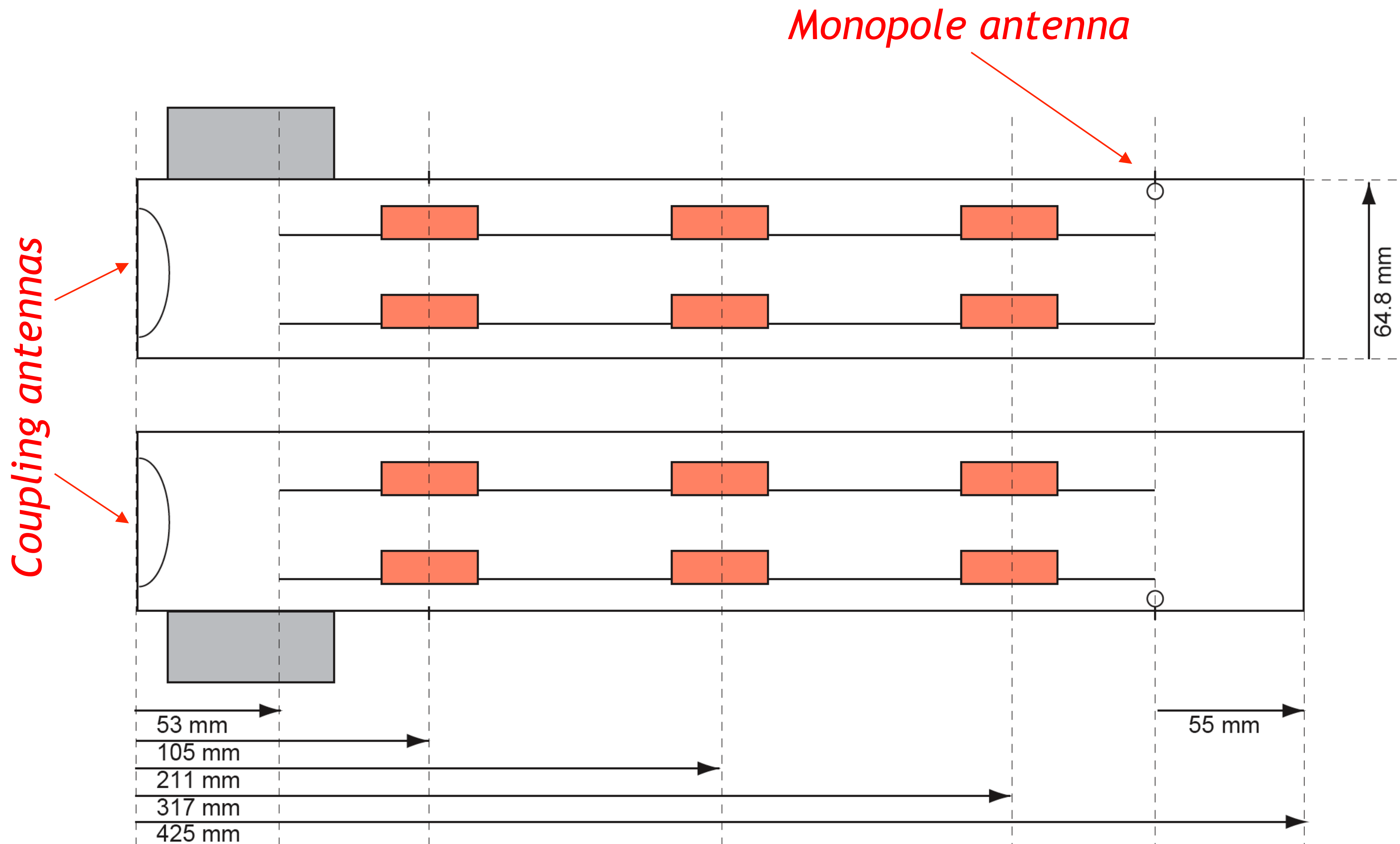
Side view

Top view

SAR inhomogeneity



Measurement of the magnetic field



Summary

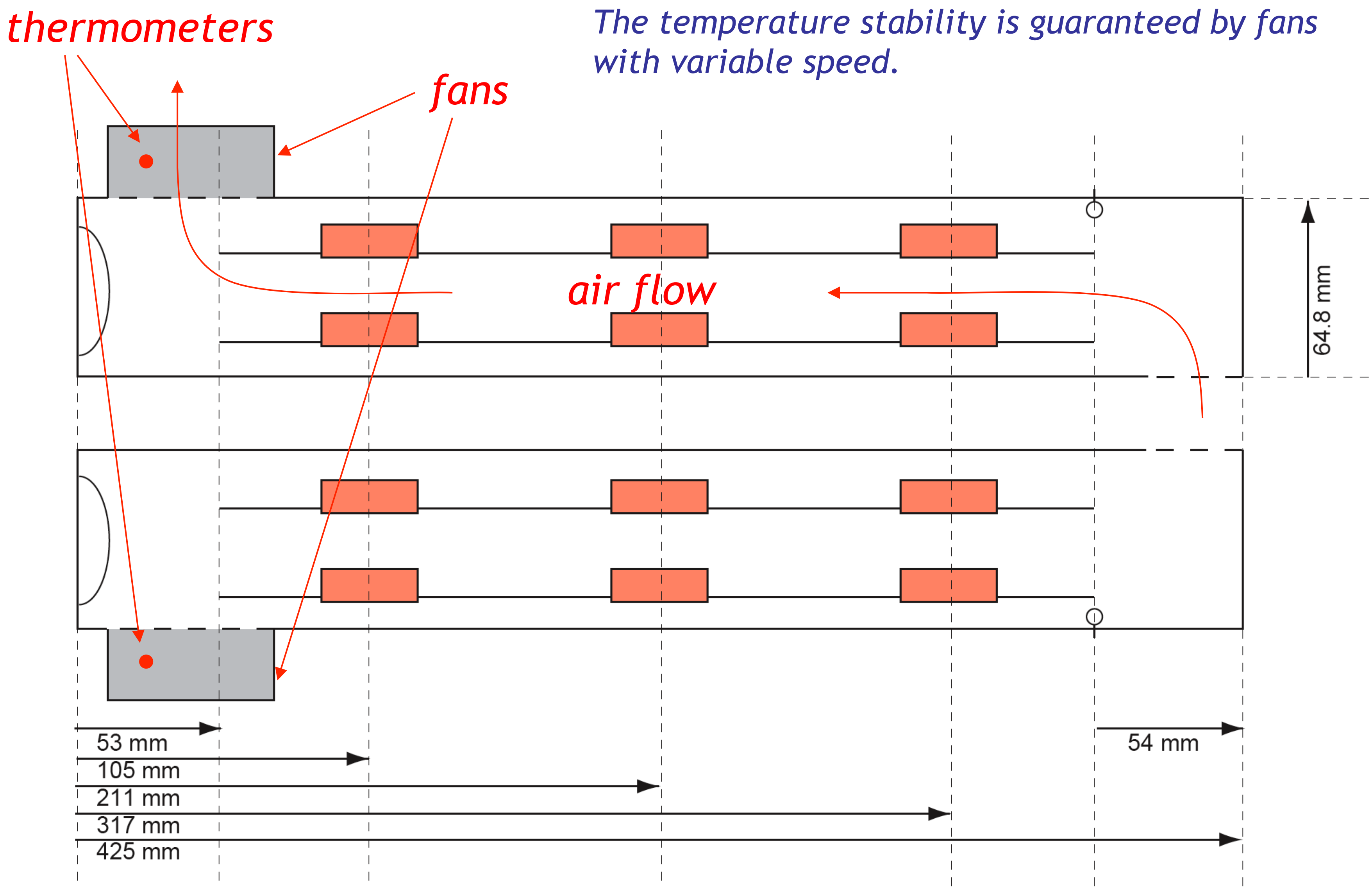
The dosimetric quantity has been parametrized w.r.t. the relevant parameters:

$$\mathrm{SAR_{bottom}} = (1.90 - 1.26h + 0.39h^2)H^2$$
$$\mathrm{SAR_{bottom}} = (2.60 - 1.84V + 0.49V^2)H^2$$
$$\mathrm{SAR_{medium}} = 0.11 + 0.39\,\mathrm{SAR_{bottom}}$$
$$\frac{\sigma_{\mathrm{SAR}}}{\mathrm{SAR}} = 7.70 + 5.94V + 0.83V^2 - 0.23V^3$$

Note: the parameters of the fits are dependent on the geometry of the device.

Temperature control

The temperature stability is guaranteed by fans with variable speed.



Temperature variation due to the EM field

$$\frac{dT_{\rm medium}}{dt} = -\frac{T_{\rm medium} - T_{\rm incub}}{\tau} + \frac{\rm SAR_{medium}}{c_{\rm w}}$$

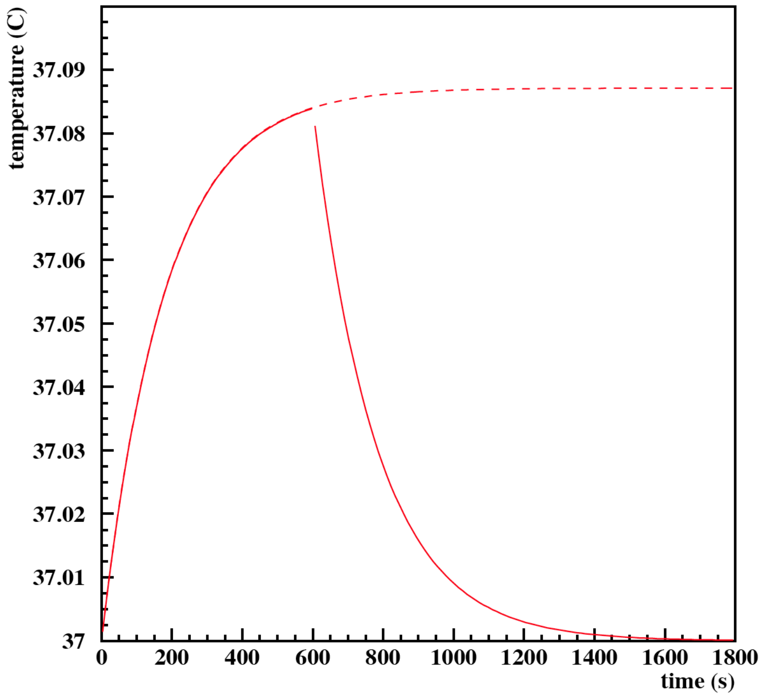
τ= heat convection time constant (180 s)
c_w=water specific heat

ON CYCLE: $$T(t) = T_{\rm incub} + \tau_{\rm on}\frac{\rm SAR_{medium}}{c_{\rm w}} - \tau_{\rm on}\frac{\rm SAR_{medium}}{c_{\rm w}}{\rm e}^{-\frac{t}{\tau_{\rm on}}}$$

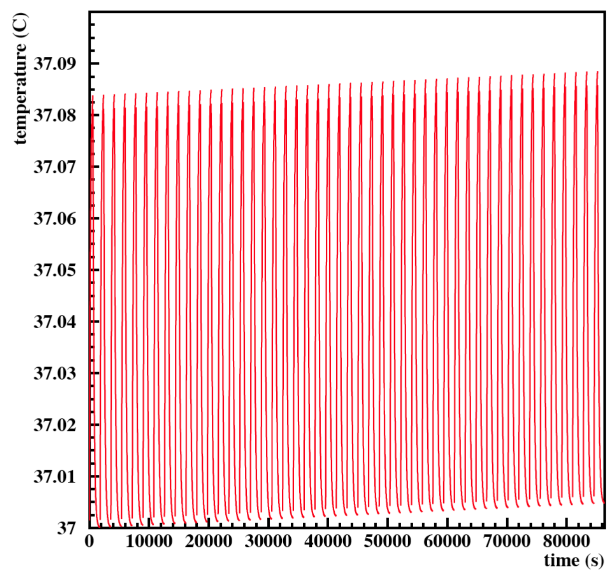
OFF CYCLE: $$T(t) = T_{\rm incub} + (T(t_0) - T_{\rm incub}){\rm e}^{-\frac{t}{\tau_{\rm off}}}$$

Temperature variation

cycle: 600 s on / 1200 s off
SAR = 2 mW/g
Total duration: 24 h

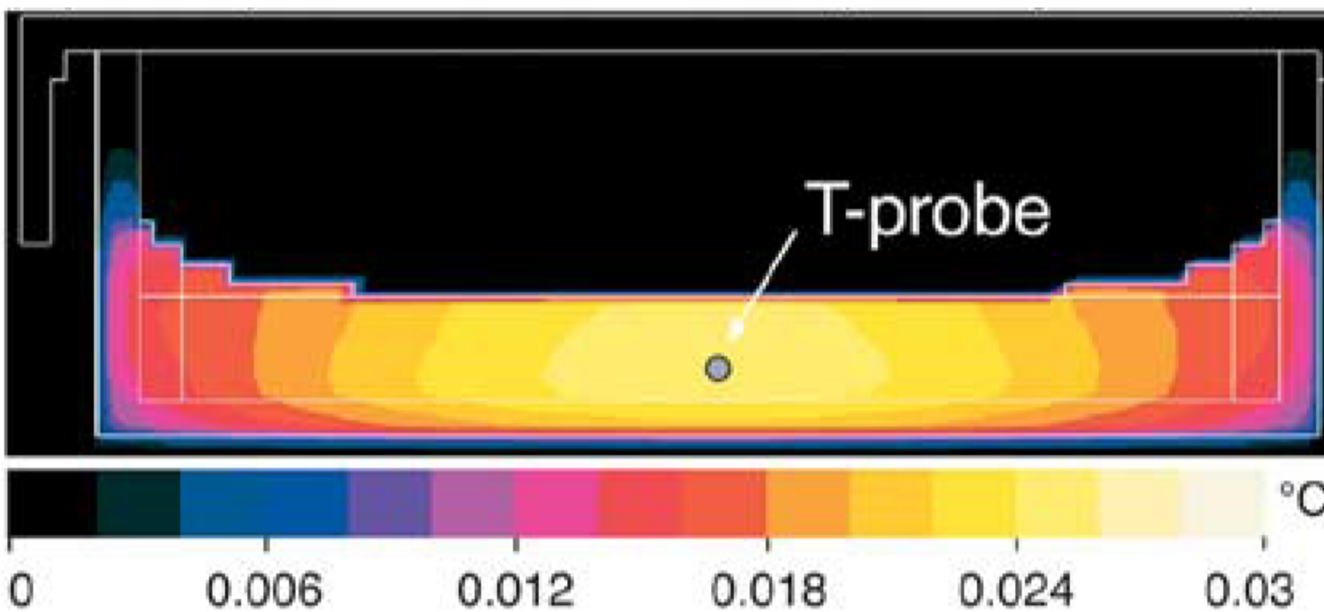


1 cycle



full experiment

Temperature inhomogeneity
SAR = 1 W/kg

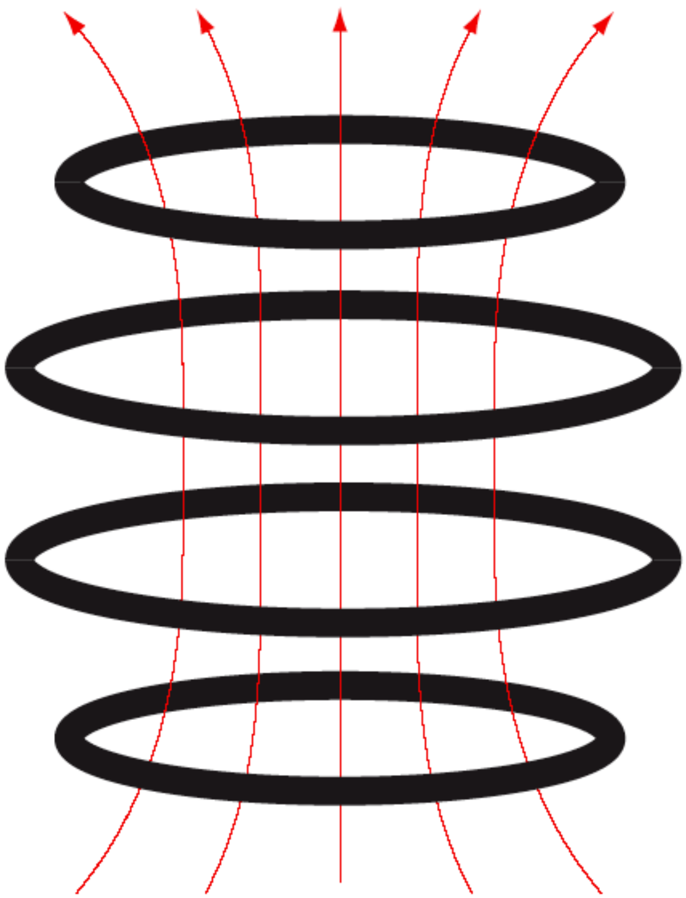


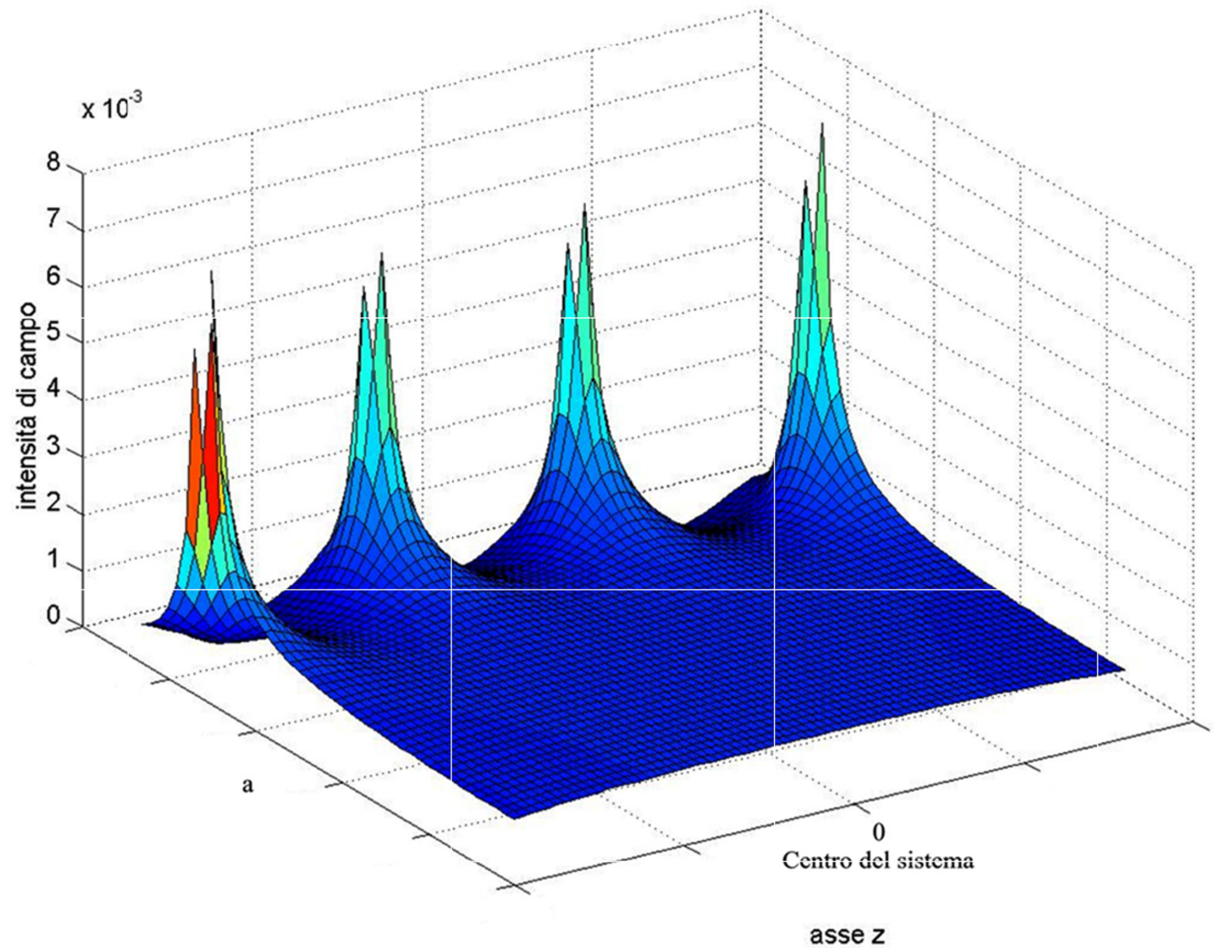
Low frequency irradiation

Because of the high conductivity of the biologic material, in the case of low frequency irradiation only the magnetic field and the currents induced by its variation are relevant.
The low frequency fields penetrate completely inside the body.

The Bologna apparatus

Solenoidal field with four coils.
All coils are doubled to allow for counter-rotating currents, i.e. sham exposure





Most important is the homogeneity of the field inside the Petri dishes