

# **New Capabilities of FDTD Modelling Software for Microwave Power Applications**

**by: W.K.Gwarek**

**QWED company**

**03-938 Warszawa, Zwyciezcow 34/2, Poland**

**and:**

**Institute of Radioelectronics**

**Warsaw University of Technology**

**00-665 Warszawa, Nowowiejska 15/19, Poland**

**E-mail: [m.celuch@ire.pw.edu.pl](mailto:m.celuch@ire.pw.edu.pl)**



# Presentation outline:

- **Applicability of EM solvers to MW heating problems**
- **Choice of EM simulation method**
- **Development of GUI**
- **Development of flexible media description**
- **Utilising important features of the FDTD solver**
- **Example 1: heating in circular waveguide**
- **Adapting the FDTD solver to the FDTD-BHM system**
- **Operating the FDTD-BHM system**
- **Example 2: thawing & heating of bread**
- **Example 3: thawing & heating of beef-burger**
- **Conclusions**

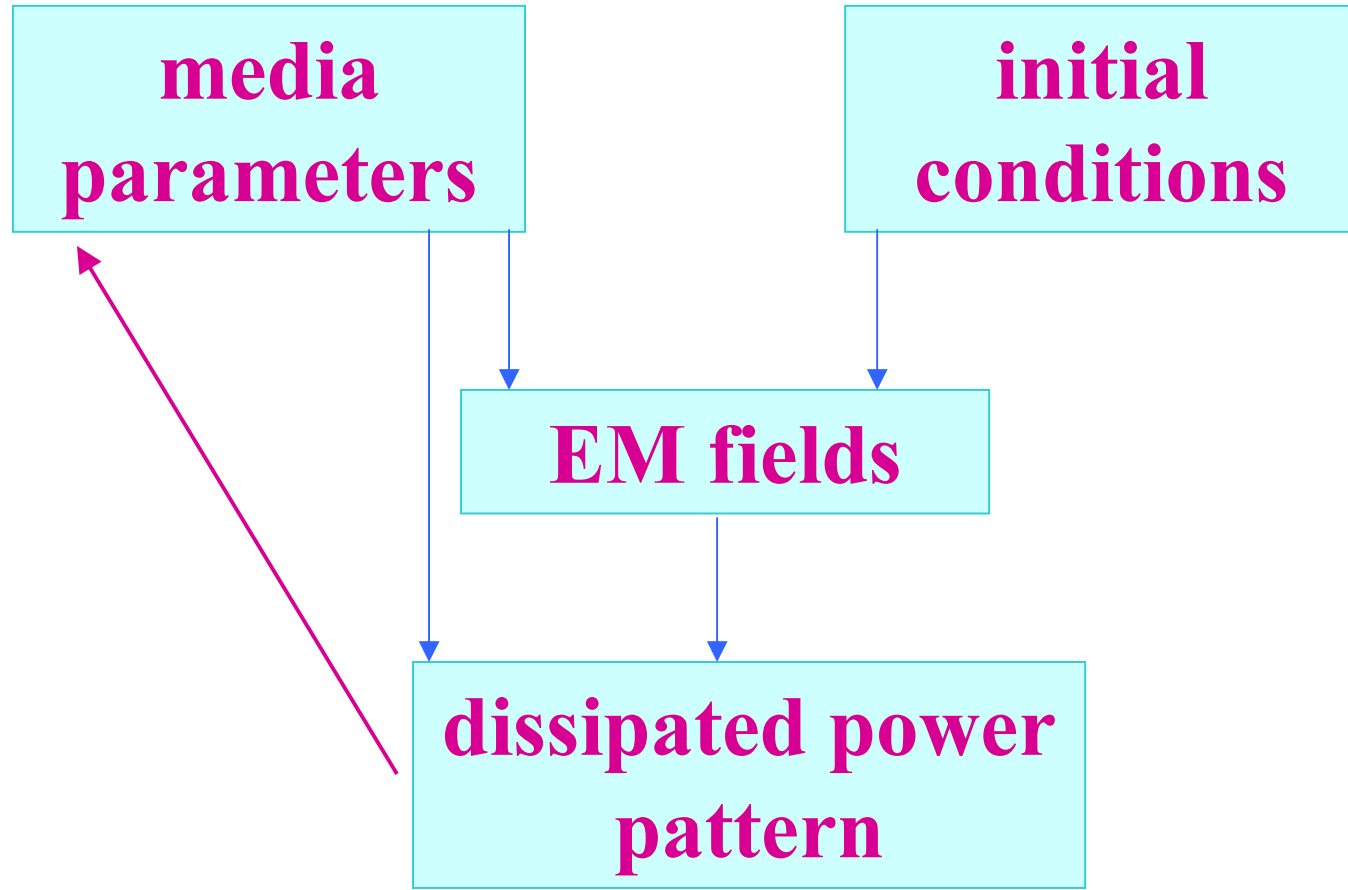
# EM solver for MW heating analysis?

- Available commercial EM solvers have been originally developed for MW communications
- In-house solvers developed in academia cannot guarantee friendly GUI (price!) and long-term support & maintenance (security of investment!)

## Goal: to adapt an existing commercial FDTD solver

- Adequacy of implemented models & procedures (and their price) for MW heating
- Adequacy of GUI (and its price) for MW heating
- New regimes and features needed for MW heating:
  - enthalpy-dependent media parameters,
  - load movement,
  - heat transfer.

# Problem overview



Hints: microwave cycle  $\sim$ nsec;  
change in media params.  $\sim$ msec..sec

# Choice of EM simulation method

## Space-discrete:

- to handle complicated cavity geometries, strongly inhomogeneous and arbitrarily shaped loads
- to easily differentiate dissipated power, temperature and physical parameters in various spots of the load

## FEM, FDTD or TLM:

- **FDTD** *increasingly* efficient for electrically *large* problems
- **TLM** formally equivalent to **FDTD** but, as we believe, somewhat less effective

	<b>FEM - direct</b>	<b>FEM – iterative</b>	<b>FDTD</b>
storage	$N^5$	$N^3$	$N^3$
CPU time	$N^7$	$N^{4..6}$	$N^4$

**FDTD - fast, memory efficient, spurious-free, wide band...**

# Development of media description

## Considerations:

- materials of very different and often very complicated thermal characteristics
- knowledge under continuous development
- confidentiality?...

## Description should be:

- flexible
- expandable by the user
- with no support needed

**Approach:** text files *medium.pmo* with tabulated listings

**Independent variable:** enthalpy density or temperature

**Dependent variable:** any / all relevant physical parameters

# Example: *beef.pmo* file

```
#Raw beef draft media
#Measurements & refinements by Per O Risman, Microtrans AB, Sweden
# DATA FROM -20 C to +80 C, dH/dV in J/cm3 NO Specheat column; reversedEnth/Temp
!Temperature      Enthalpy          EPx      EPy      EPz      SIGx      SIGy      SIGz
# Data deg C      J/cm3              S/m
-20                0                  4.9      4.9      4.9      0.064     0.064     0.064
-15                14.0              5.5      5.5      5.5      0.093     0.093     0.093
-10                34.4              6.1      6.1      6.1      0.153     0.153     0.153
-5                 71.4              12.3     12.3     12.3     0.573     0.573     0.573
-3                 110.4             22.0     22.0     22.0     1.118     1.118     1.118
-2.2               144.4             30       30       30       1.636     1.636     1.636
-1.6               192.4             42       42       42       2.113     2.113     2.113
-1.3               240.4             46       46       46       2.385     2.385     2.385
-1.1               274.4             48.9     48.9     48.9     2.426     2.426     2.426
-1.0               288.4             49.2     49.2     49.2     2.440     2.440     2.440
10                 327.9             48.9     48.9     48.9     2.317     2.317     2.317
20                 382.9             48.2     48.2     48.2     2.194     2.194     2.194
35                 450.4             46.9     46.9     46.9     2.072     2.072     2.072
50                 517.9             45.5     45.5     45.5     1.949     1.949     1.949
65                 585.4             43.6     43.6     43.6     1.922     1.922     1.922
80                 652.9             41.7     41.7     41.7     1.908     1.908     1.908
```

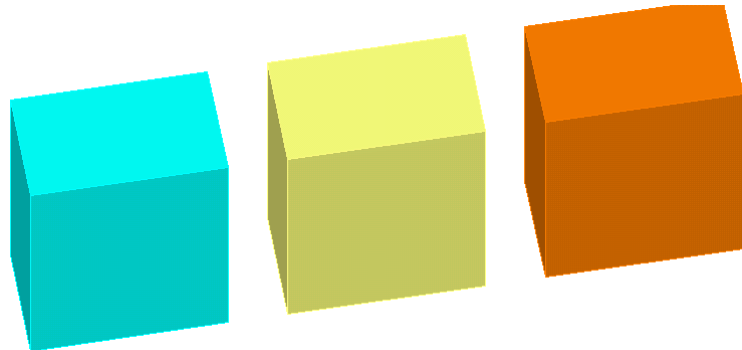
**Accepted keywords:** *Enthalpy, Temperature, EPx, EPy, EPz, SIGx, SIGy, SIGz, MUx, MUy, MUz, MSIGx, MSIGy, MSIGz, Density, SpecHeat.*

# Utilising key features of FDTD solver

- *Conformal* meshing and *conformal* FDTD algorithms (in-house models of curved boundaries, media interfaces, singularities)
- Convenient GUI with *libraries* of parameterised objects
- Excitation with user-defined source type, pulse type, available power,...
- Extraction of return loss
- Electric, magnetic and metal losses
- Extensive display of *absolute values* of fields & power
- Extraction of *average* dissipated power
- Batch operation, freeze function, multithread options...



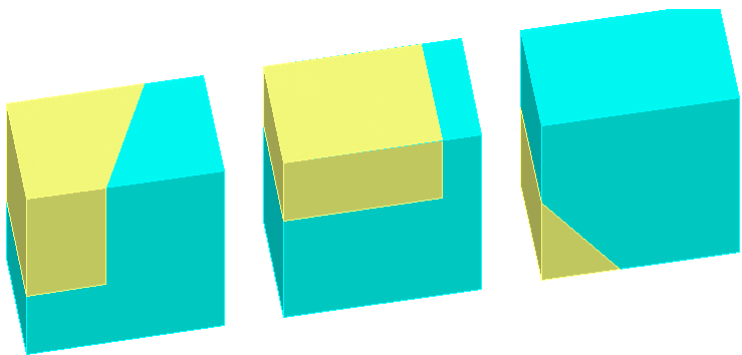
# Standard FDTD cells



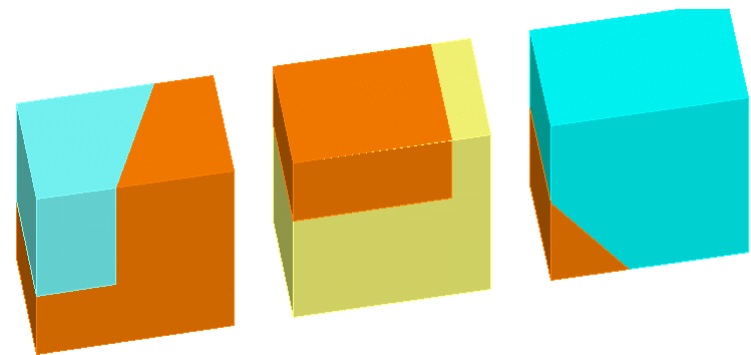
air dielectric metal

→ “stair-case” FDTD

# Conformal cells



dielectric media interfaces



metal boundaries

# Quick notation & *lcs*m pre-processor

## Standard FDTD notation:

$${}_{k,l,m+0.5} E_z^{n+1} = {}_{k,l,m+0.5} E_z^n + \{ [{}_{k+0.5,l,m+0.5} H_y^{n+0.5} - {}_{k-0.5,l,m+0.5} H_y^{n+0.5}] (\Delta t / \Delta x) \\ + [{}_{k,l-0.5,m+0.5} H_x^{n+0.5} - {}_{k,l+0.5,m+0.5} H_x^{n+0.5}] (\Delta t / \Delta y) \} / ({}_{k,l,m+0.5} \epsilon_z \epsilon_0)$$

prescripts - spatial location; superscripts – time instants;

$\Delta x$ ,  $\Delta y$ ,  $\Delta z$ ,  $\Delta t$  - discretisation steps in space and time

## Our notation:

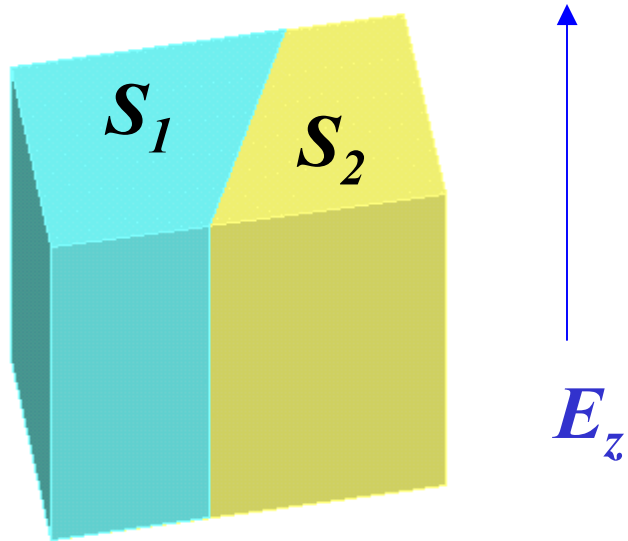
$${}_{k,l,m+0.5} e_z^{n+1} = {}_{k,l,m+0.5} e_z^n + [{}_{k+0.5,l,m+0.5} h_y^{n+0.5} - {}_{k-0.5,l,m+0.5} h_y^{n+0.5} \\ + {}_{k,l-0.5,m+0.5} h_x^{n+0.5} - {}_{k,l+0.5,m+0.5} h_x^{n+0.5}] / {}_{k,l,m+0.5} c_z$$

$$e_z = E_z \Delta z / \sqrt{\eta}, \quad h_x = H_x \Delta x / \sqrt{\eta}, \quad h_y = H_y \Delta y / \sqrt{\eta}; \quad c_z = \epsilon_z (\Delta x \Delta y) / (\Delta z \Delta t c);$$

$\eta$  - free space impedance;  $c$  – speed of light

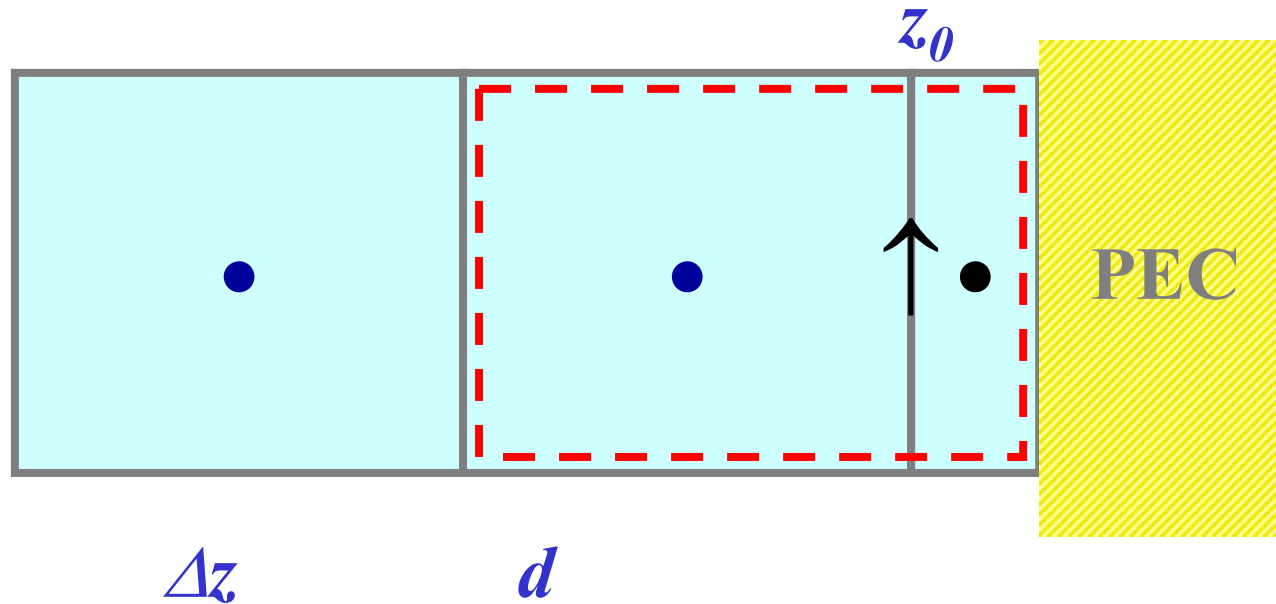
# Offset dielectric interfaces

Effective dielectric constant based on local quasistatic parallel-series connections, e.g.:



$$c_z = (\varepsilon_{z1} S_1 + \varepsilon_{z2} S_2) / (\Delta z \Delta t c)$$

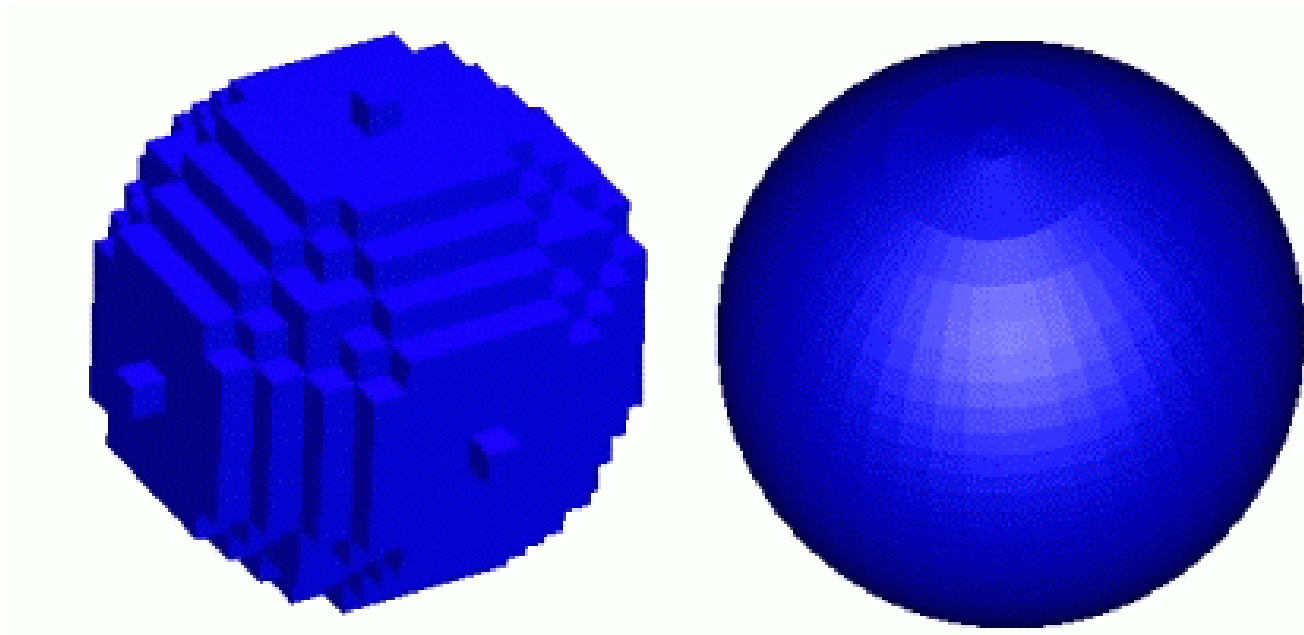
# Offset metal boundaries



1. Stair-case - neglect small cell
2. Brute force conformal - leave small cell
3. **Advanced conformal - merge cells**

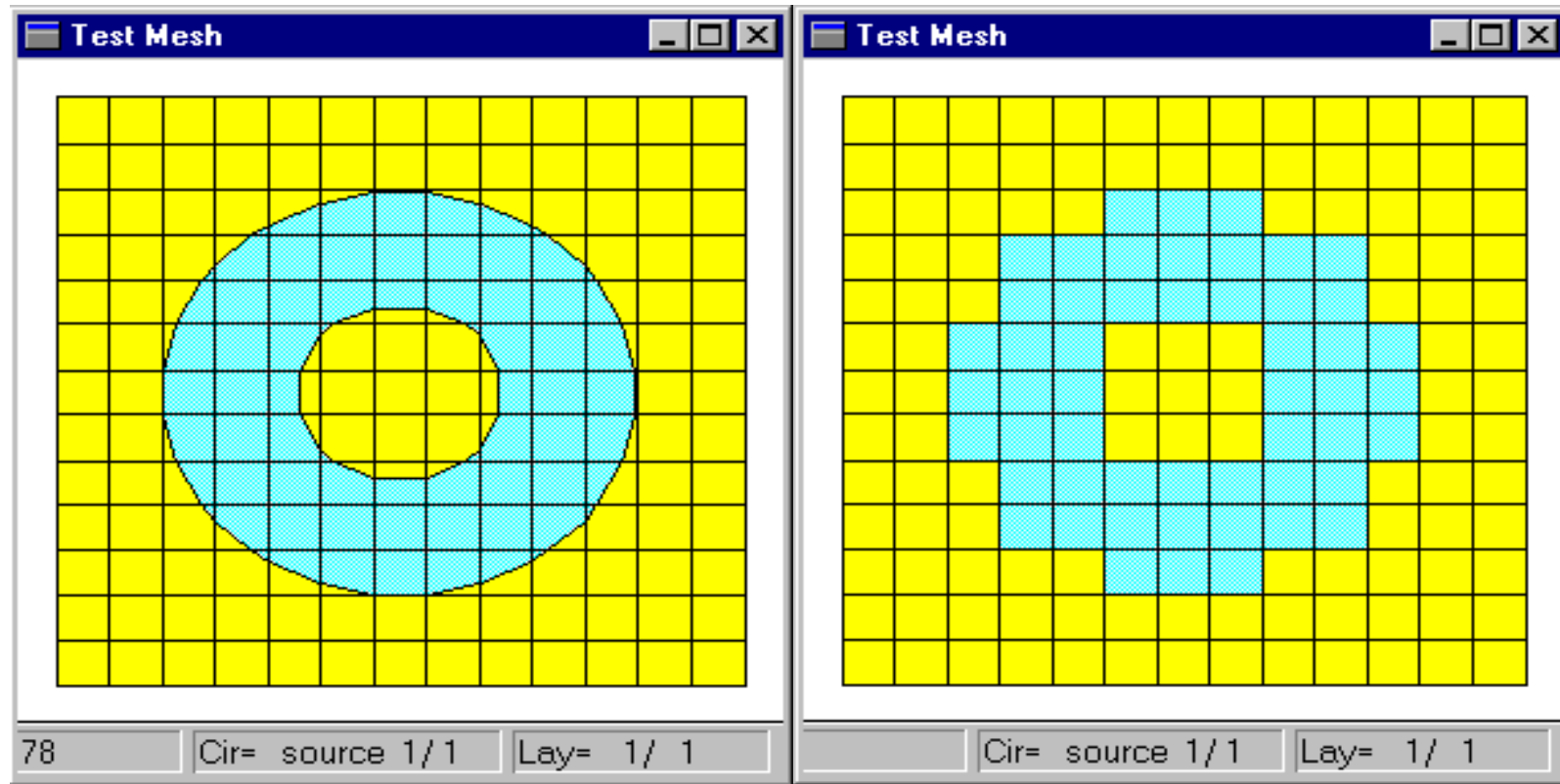
*Attention:*  $\Delta t < a_{min} / (c \sqrt{3})$

# Conformal versus stair-case mesh



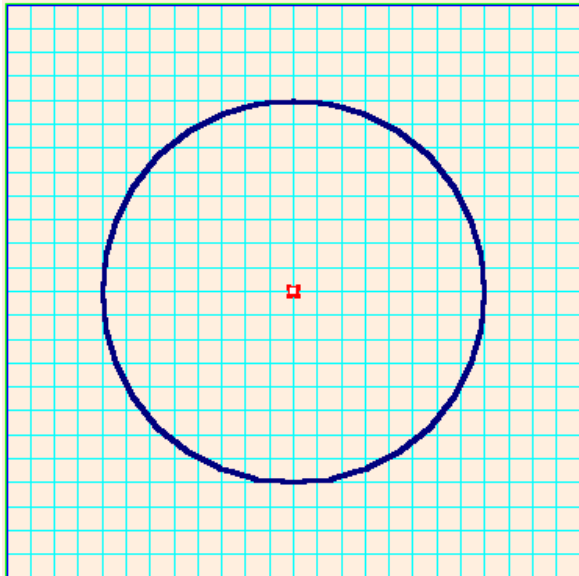
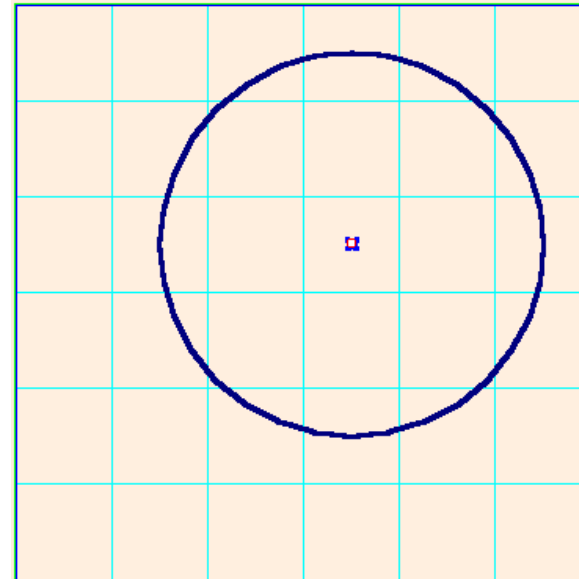
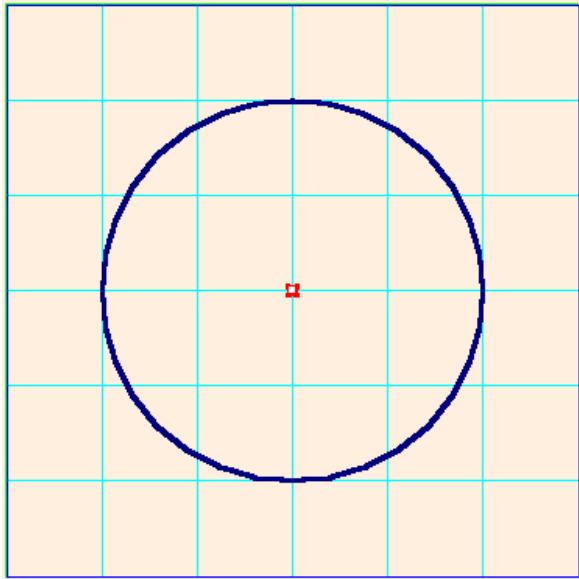
e.g.: potato, egg

# Conformal versus stair-case mesh



e.g. cross-section through: coaxial line, hot-dog, donut

# Meshing a cylindrical object

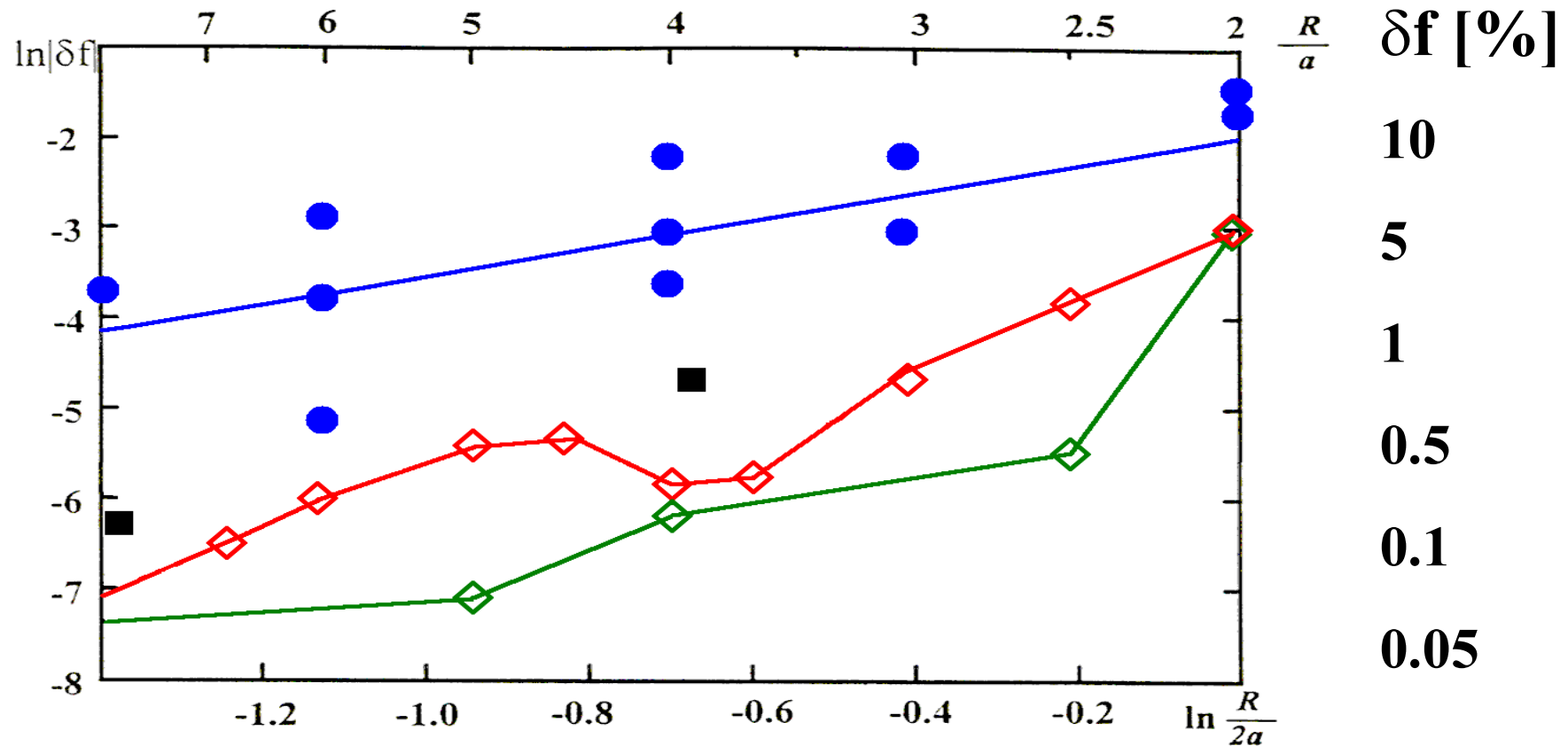


**e.g. cross-section through:**

- **glass plate**
- **hamburger**
- **pizza**

# Analysing a cylindrical resonator

No. of cells per radius 8..2



stair-case

no or simple merging (Railton & Schneider, *MTT Trans.* Jan.1999)

directional cell merging

linearised directional cell merging



# User interface: some basic libraries

**Browse UDOs C:\Program Files\QWED\QW\_3D\v21Xmas\Local\Qw\_edi\elib\basic - Basic shapes for various applications**

<b>cyvao</b> 	<b>cyvo</b> 	<b>cyvor</b> 	<b>el</b> 	<b>htapb</b> 	<b>lic</b> 
Part of a vertical cylinder (MP/BP)	Vertical cylinder (MP/BP)	Rotated vertical cylinder (MP/BP)	Full ellipsoid sliced with combined or regular elements (BP)	Rectangular waveguide horizontal taper (BP)	Horizontal curved cylinder (BP)
<b>lih</b> 	<b>lirot</b> 	<b>lt</b> 	<b>ltrot</b> 	<b>rounre</b> 	<b>solid</b> 
Horizontal cylinder (BP)	Inclined cylinder (BP)	Horizontal taper (BP)	Inclined taper (BP)	Rectangle with rounded corners	Rectangular waveguide (MP/BP)
<b>sp</b> 	<b>sph</b> 	<b>torusv</b> 	<b>torw</b> 	<b>tvao</b> 	<b>tvo</b> 
Full sphere sliced combined (BP) or regular elements	Full sphere sliced combined (BP) or regular elements	Local torus (BP)	Local torus (BP)	Part of a vertical taper (MP/BP)	Vertical taper (MP/BP)

**Browse UDOs C:\Program Files\QWED\QW\_3D\v21Xmas\Local\Qw\_edi\elib\coax - Horizontal coaxes IN METAL**

<b>hornhc</b> 	<b>hornhca</b> 	<b>hornhcr</b> 	<b>hornhcra</b> 
Circular waveguide horn, horizontal in metal (BP)	Circular horn antenna, horizontal in air (BP)	Circular waveguide horn, horizontal in metal (BP) with ridges	Circular waveguide horn, horizontal in metal (BP) with user-defined ridge
<b>hornvcara</b> 	<b>hornvr</b> 	<b>hornvra</b> 	<b>patch1</b> 
CirC. horn antenna with user-defined ridges, vertical in air (BP)	Rectangular waveguide horn (vertical) with ridges	Rectangular wg. horn vertical with user-defined ridges (BP)	Circular patch antenna

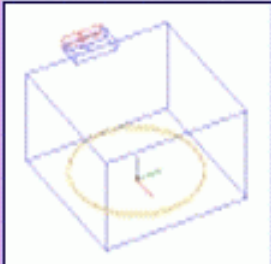
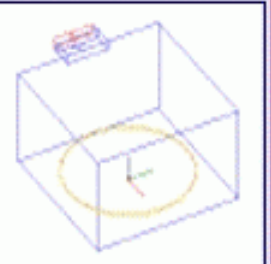
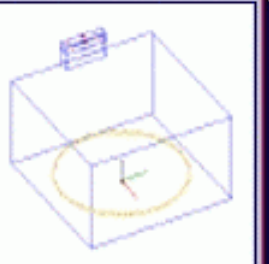
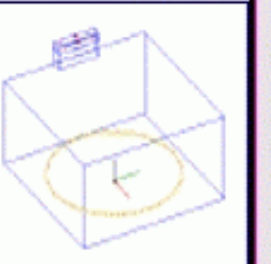
<b>crh</b> 	<b>crv</b> 	<b>ct</b> 
Tee junction of a cylindrical and horizontal rectangular waveguide (BP)	Tee junction of a cylindrical and vertical rectangular waveguide (BP)	Tee junction of 2 horizontal cylinders (BP)
<b>cx4r</b> 	<b>cx6r</b> 	<b>rch</b> 
Junction of 4 horizontal cylinders of different diameters (BP)	Junction of 6 perpendicular cylinders of different diameters (BP)	Tee junction of a rectangular and horizontal cylindrical waveguide (BP)

<b>ct1d</b> 	<b>ct2d</b> 	<b>ct3d</b> 
Tee junction of coaxial lines with 1 dielectric (BP)	Tee junction of two coaxial lines with 2 dielectrics (BP)	Tee junction of coaxial lines with 3 dielectrics (BP)
<b>cx1d</b> 	<b>cx2d</b> 	<b>cx3d</b> 
Junction of coaxial lines with 1 dielectric (BP)	Junction of coaxial lines with 2 dielectrics (BP)	Junction of coaxial lines with 3 dielectrics (BP)

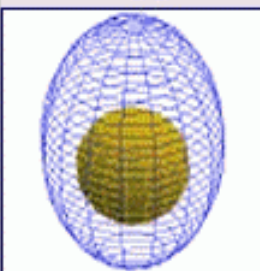



<b>lic1d</b> 	<b>lic2d</b> 	<b>lic3d</b> 
Curved coaxial line with 1 dielectric (BP)	Curved coaxial line with 2 dielectrics (BP)	Curved coaxial line with 3 dielectrics (BP)
<b>lih1d</b> 	<b>lih2d</b> 	<b>lih3d</b> 
Coaxial line with 1 dielectric (BP)	Coaxial line with 2 dielectrics (BP)	Coaxial line with 3 dielectrics (BP)

# Some specialised libraries

Browse UDOs C:\Program Files\QWED\QW\_3D\v21Xmas\Local\Qw\_edi\elib\ovens

ovenh	ovenhp	oveny	ovenyp
			
Microwave domestic oven with horizontal feeding waveguide	Microwave domestic oven, horizontal feed, with port file & mesh co	Microwave domestic oven with vertical feeding waveguide	Microwave domestic oven, vertical feed, with port file & mesh control

Browse UDOs C:\Program Files\QWED\QW\_3D\v21Xmas\Local\Qw\_edi\elib\food

egg	pizza	sausage	sausager
			
Egg (BP)	2-layered pizza	Sausage with rounded ends (BP)	Curved sausage with rounded ends (BP)

Add Object C:\Program Files\QWED\QW\_3D\v21...

Parameters	Value
Name	egg
White radius along x-axis	20
White radius along y-axis	20
White radius along z-axis	30
Yolk diameter	25
Sectors	16
White medium	eggwhite
Yolk medium	egg yolk
Special plane	Y
2 - combined; <0,1> - reg	2

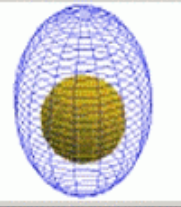
Origin

X

Y

Z

View



Page

Prev

1 of 1

Next

F -> D

Cancel

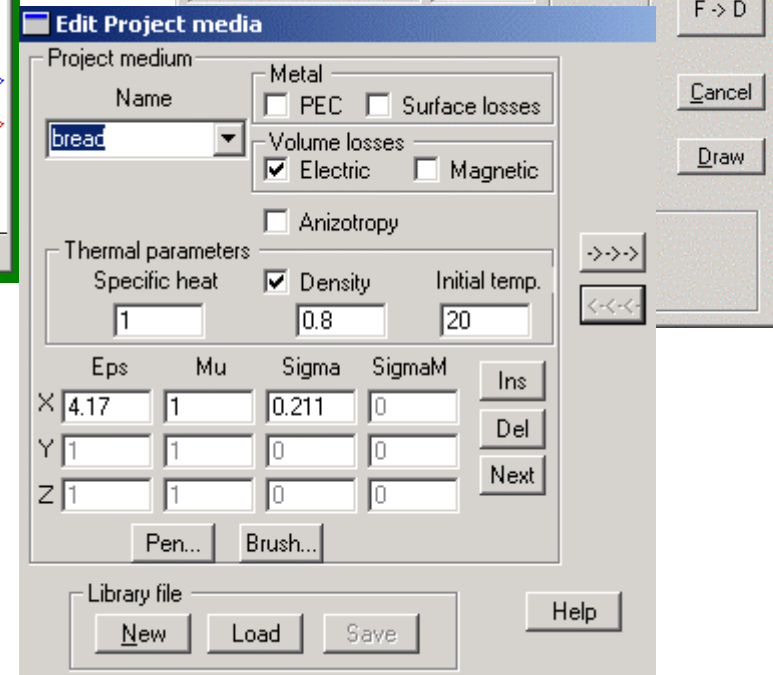
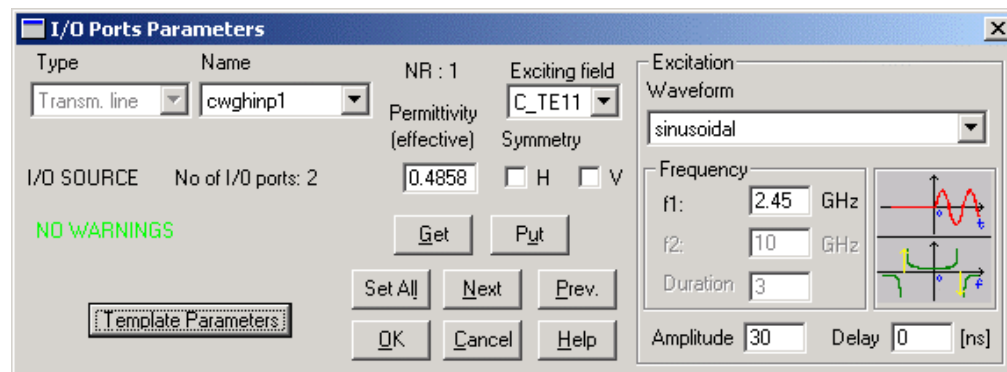
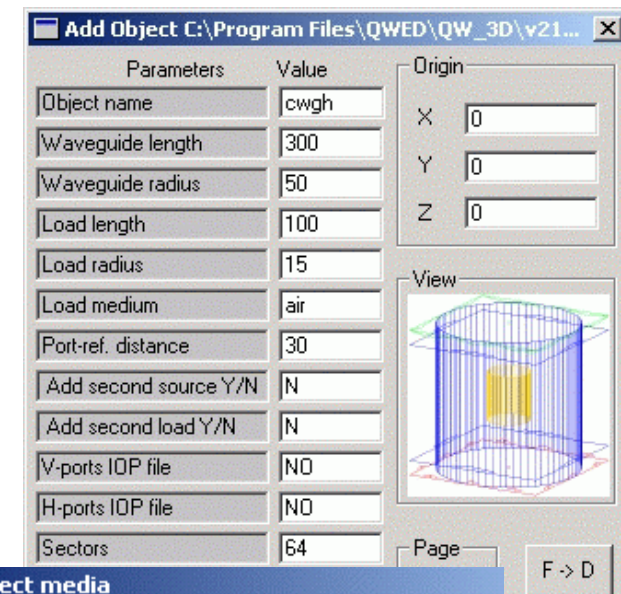
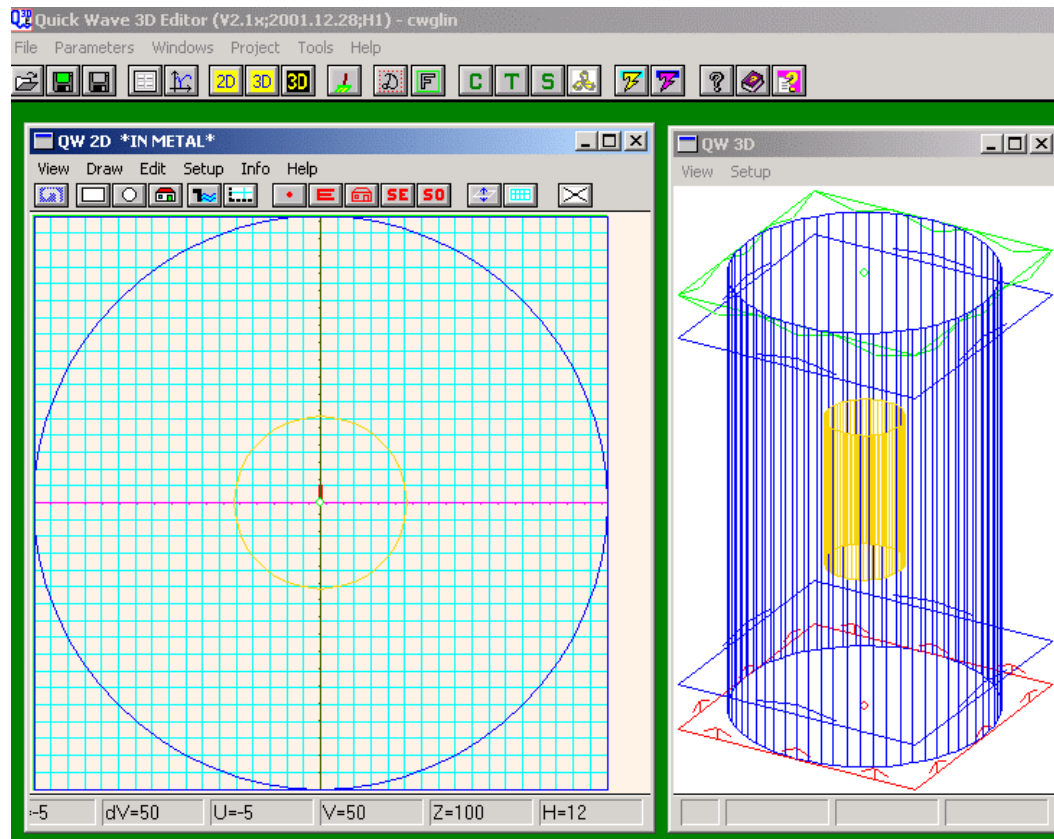
Draw

Description

Egg (BP)

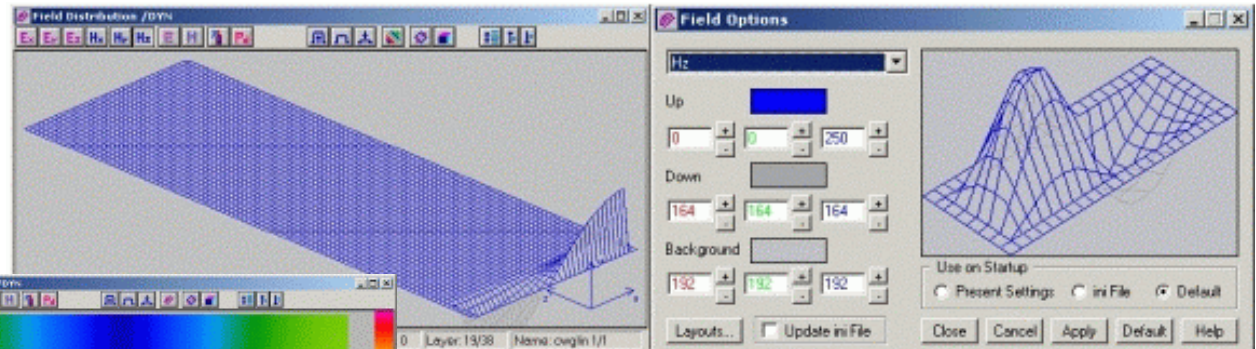


# Example 1: heating in circular guide

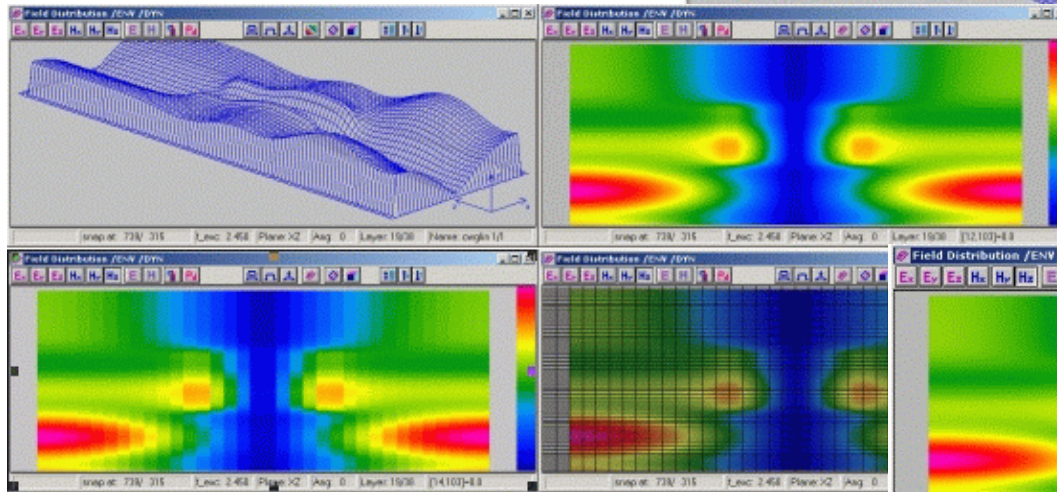


# Example 1: longitudinal H-field

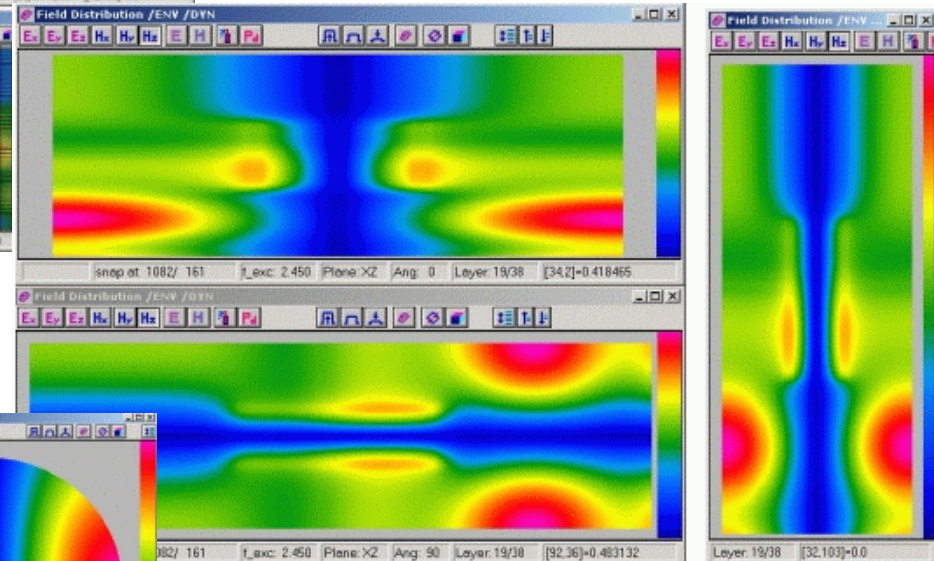
transients & display options



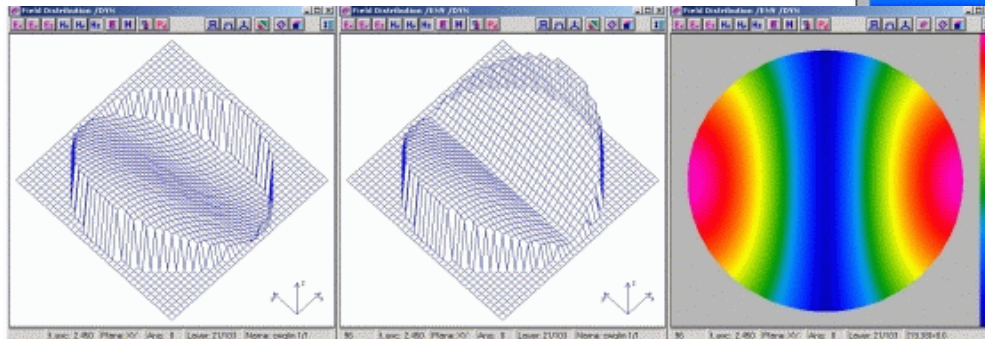
steady-state envelopes



rotating options



cross-sectional mode pattern





# Example 1: heating patterns

Dissipated power

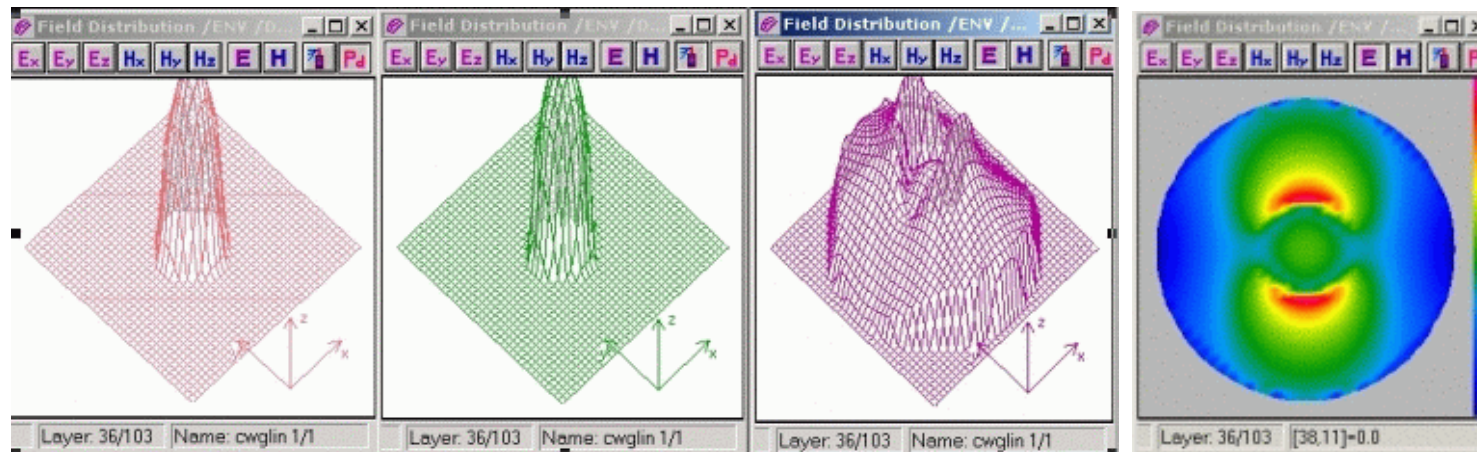
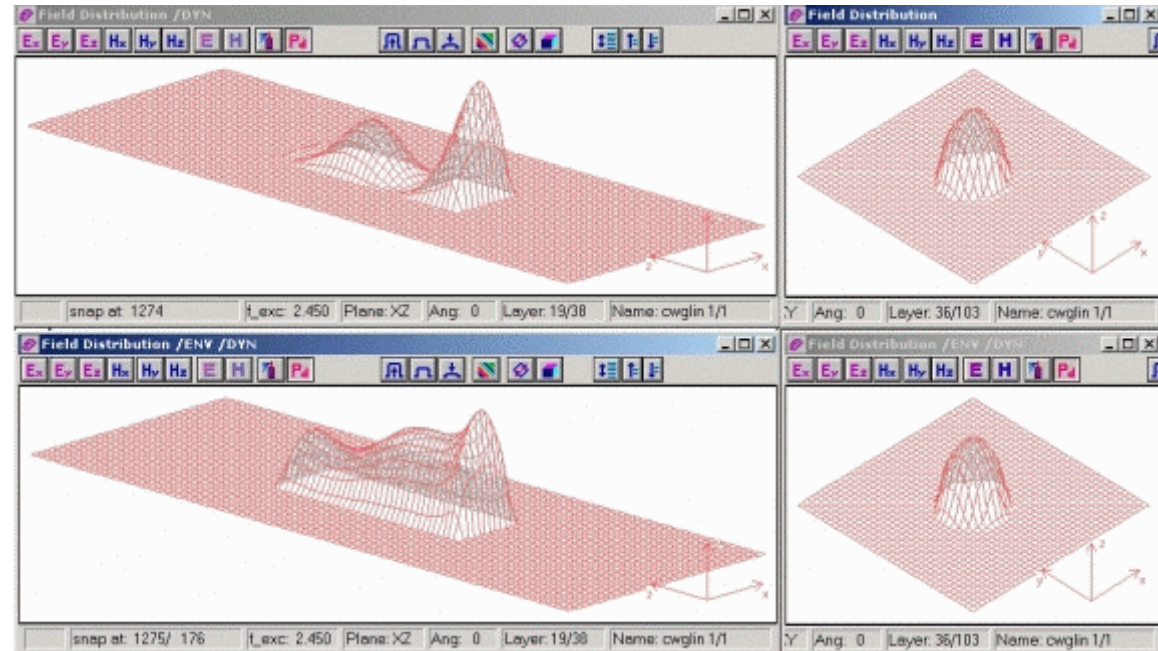
instantaneous

envelope

Power

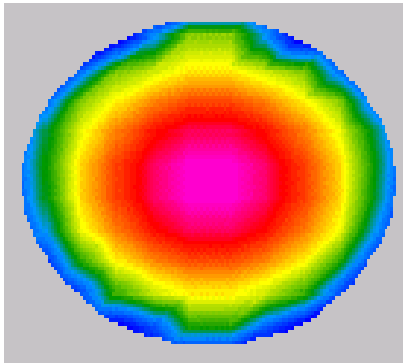
SAR

total E-field

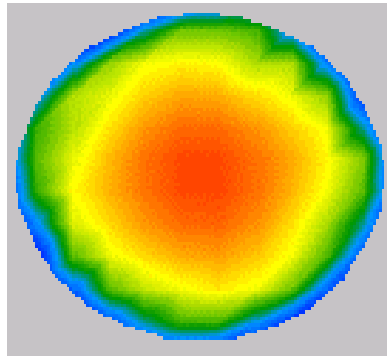


# Example 1: circular polarisation

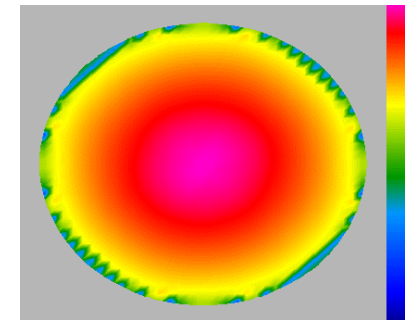
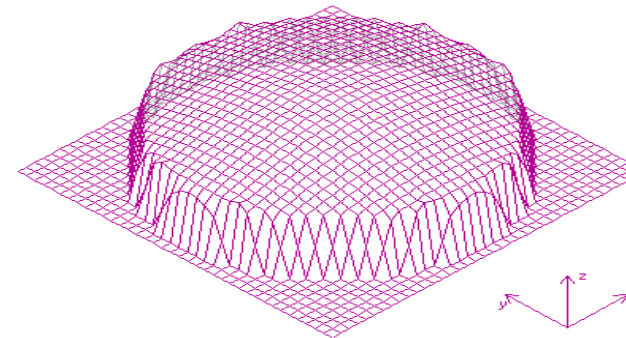
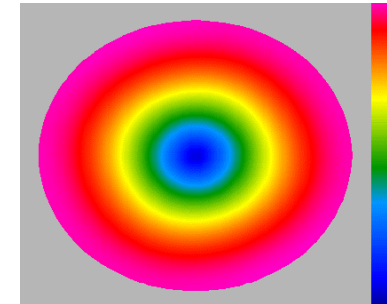
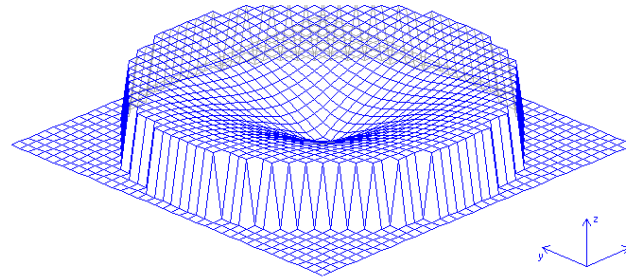
Power envelopes:



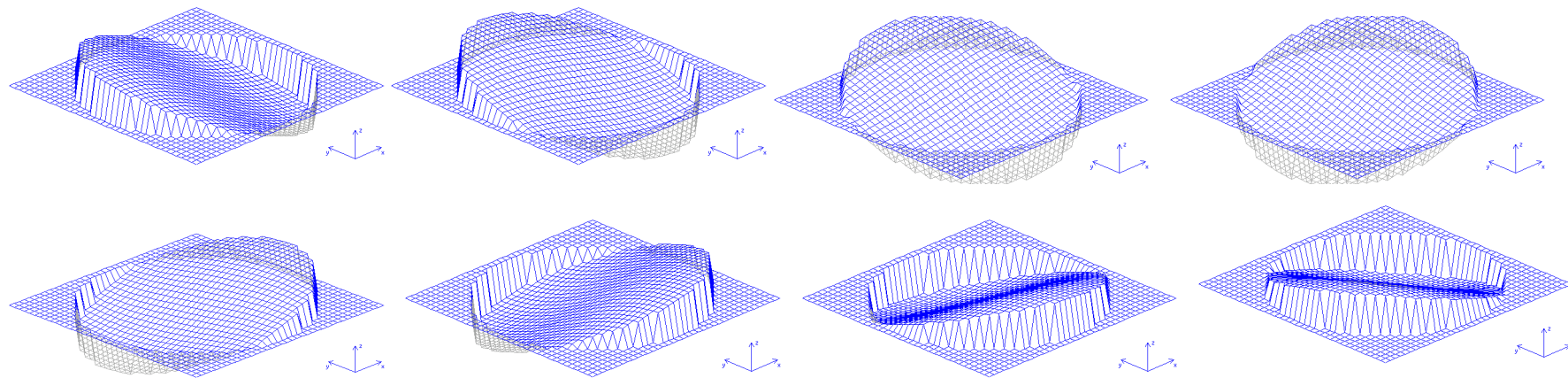
linear



circular



Instantaneous H:



Envelopes: longitudinal H, total E

# Adapting the FDTD solver to thermal operation

**QW-Editor - minor changes - allow setting of:**

- **initial temperature for all media**
- **default specific heat for all media**

**QW-Simulator - major changes:**

- **read medium parameters from *\*.pmo* file, if exists**
- **re-compile *lcs*m matrices in each EM steady state**

# Operating the FDTD-BHM system

1. Run FDTD with sinusoidal source until **EM steady state**
2. Produce 3D pattern of **average** dissipated power  $P^m(x,y,z)$ .
3. Upgrade the enthalpy (enthalpy density) distribution by:

$$H^{m+1}(x,y,z) = H^m(x,y,z) + P^m(x,y,z) \Delta\tau$$

where  $\Delta\tau$  user-defined heating time.

4. Upgrade the temperature distribution in each FDTD cell:
  - a)  $T^{m+1}(x,y,z) = T [H^{m+1}(x,y,z)]$
  - b)  $T^{m+1}(x,y,z) = T^m(x,y,z) + P^m(x,y,z) \Delta\tau / (\rho^m(x,y,z) C^m(x,y,z))$
5. Repeat *lcs*m compilation. For each cell at  $(x,y,z)$ , read new media parameters from \*.*p*mo, as a function of  $H^{m+1}(x,y,z)$  or  $T^{m+1}(x,y,z)$  of this cell.
6. Continue FDTD analysis from previous to new steady state.



# Reading new media parameters

Consider  $\varepsilon_z^{m+1}(x,y,z)$ :

a) *medium.pmo* exists,  $\varepsilon_z$  and  $H$  are listed:

$$\varepsilon_z^{m+1}(x,y,z) = \varepsilon_z [H^{m+1}(x,y,z)]$$

b) *medium.pmo* exists,  $\varepsilon_z$  is listed,  $H$  is not listed:

$$\varepsilon_z^{m+1}(x,y,z) = \varepsilon_z [T^{m+1}(x,y,z)]$$

c) *medium.pmo* does not exist or  $\varepsilon_z$  is not listed:

default  $\varepsilon_z$  (as defined in QW-Editor)

maintained.

linear interpolation between listed points,

flat extrapolation outside listed range

# How to choose $\Delta\tau$

→ system stability and rate of convergence

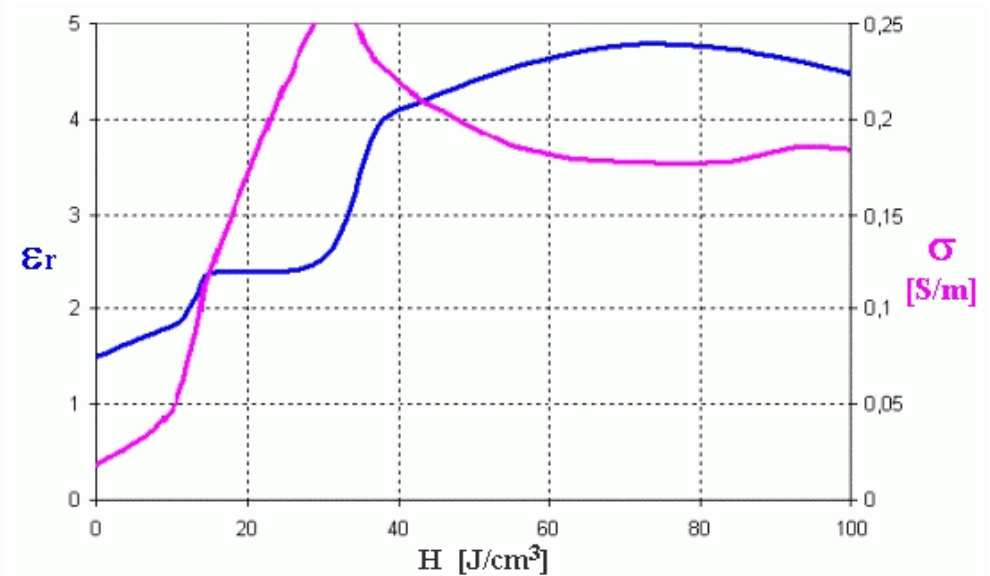
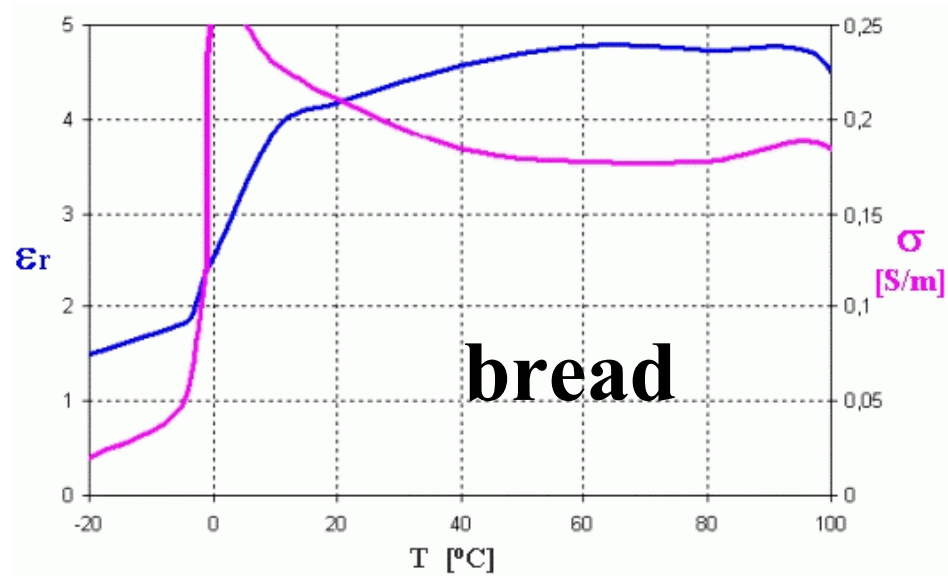
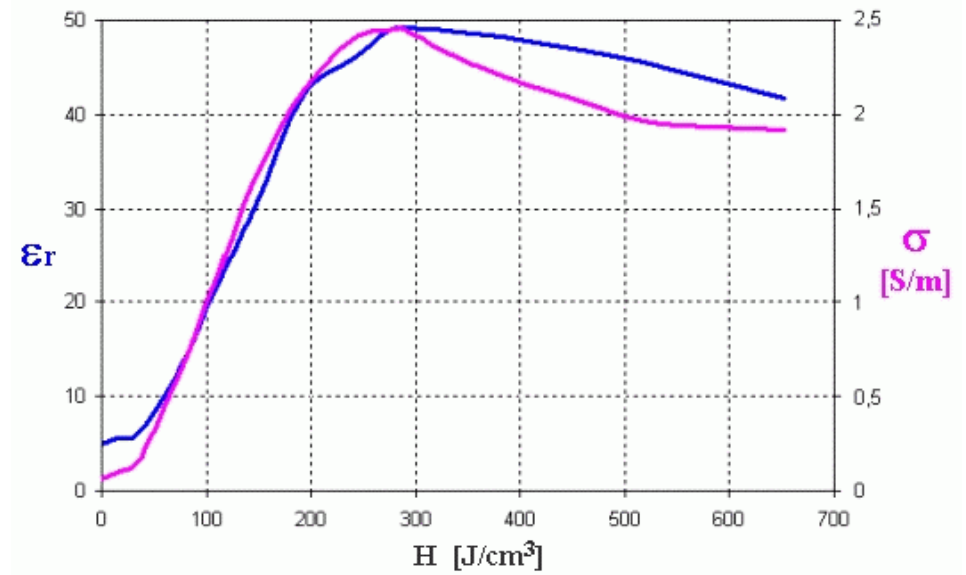
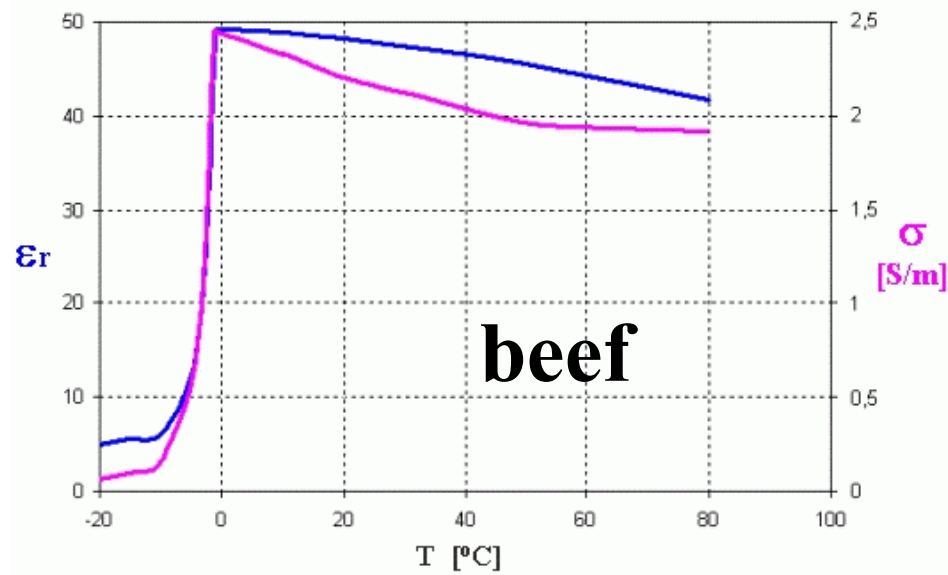
**Hint: no scaling involved!**

$\Delta\tau$  - physical heating time in [sec]

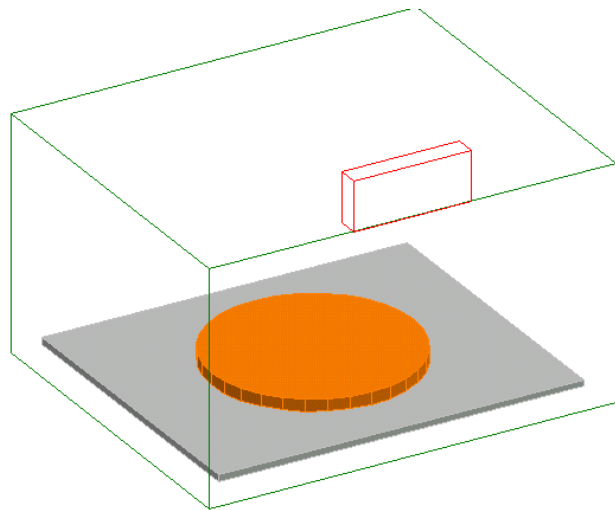
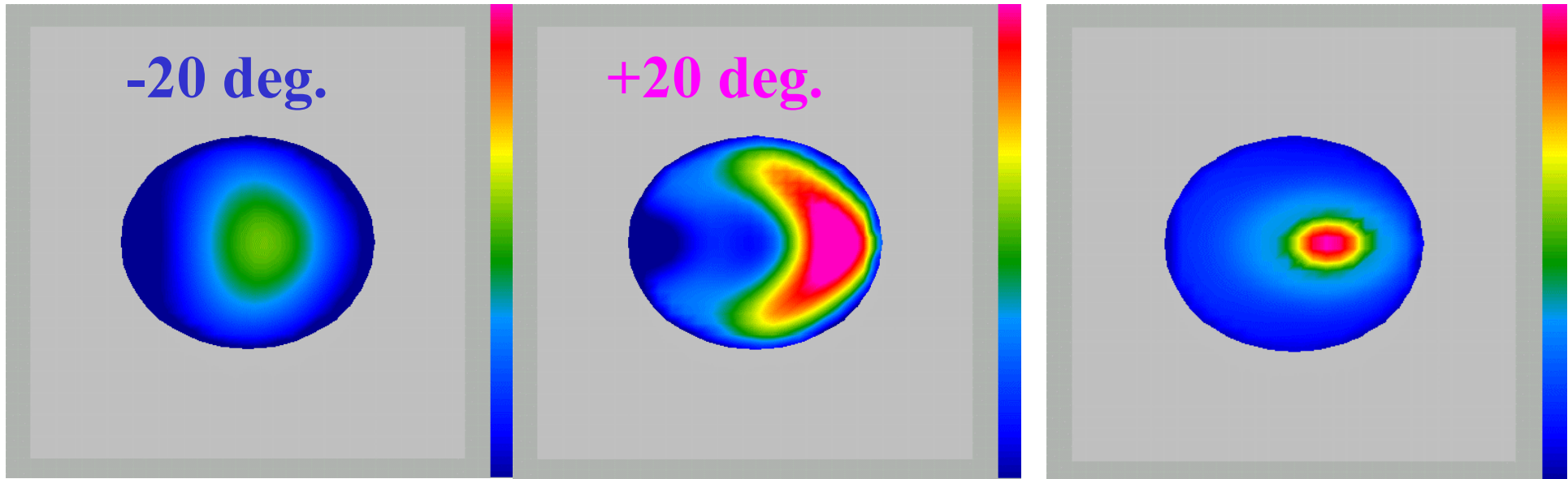
source available power in [W] is set by the user

- watch power patterns over the scenario
- consult sketches of media characteristics
- verify new media parameters over the scenario
- “add” more heat:  $\Delta\tau_1 + \Delta\tau_2$
- “unburn” overcooked meal:  $\Delta\tau_1 - \Delta\tau_2$

# Considered characteristics



# Example 2: thawing & heating bread



cavity 204x204x228mm,  
plate 180x216x6mm  
at  $z=12\text{mm}$ ,  $\epsilon'=6$   
feed 12x70mm,  
source 2.45GHz, 625W,  
bread  $r=60\text{mm}$ ,  $h=6\text{mm}$

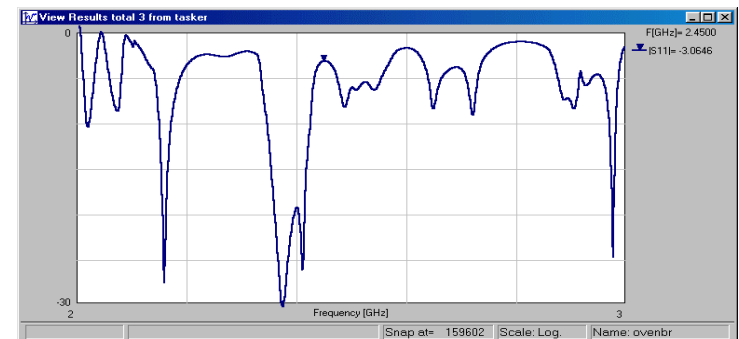
Return loss at +20 deg.

**FDTD-BHM result**

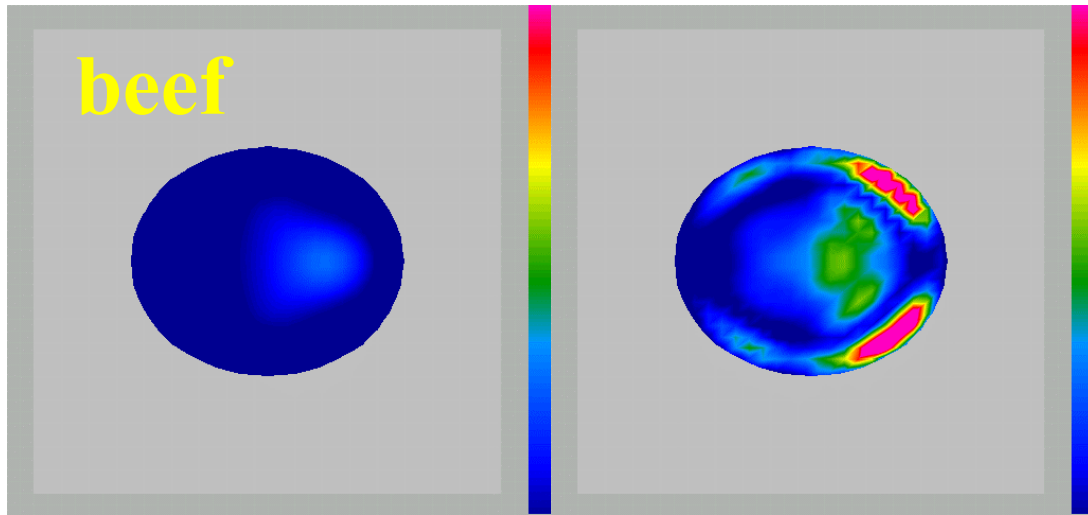
**7 thermal iter., each 2 sec.**

**frozen edge -10 deg.**

**hot spot +33 deg.**

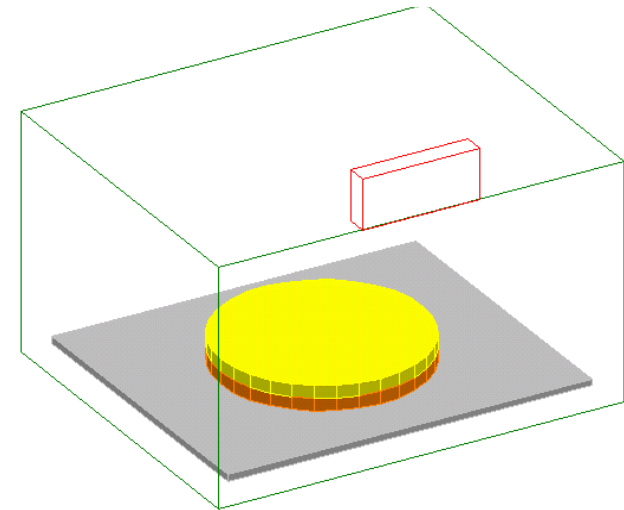


# Example 3: beefburger

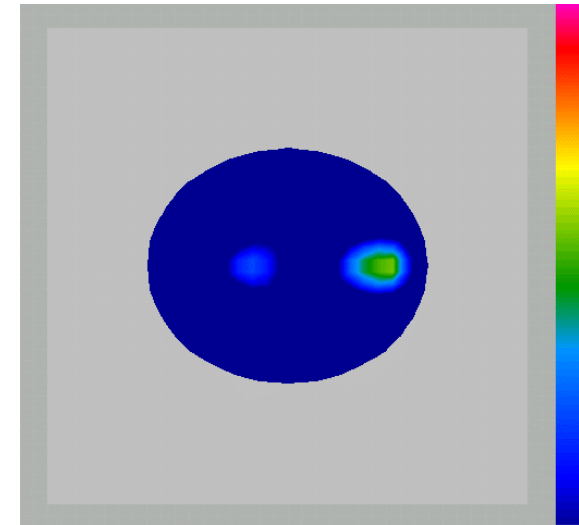
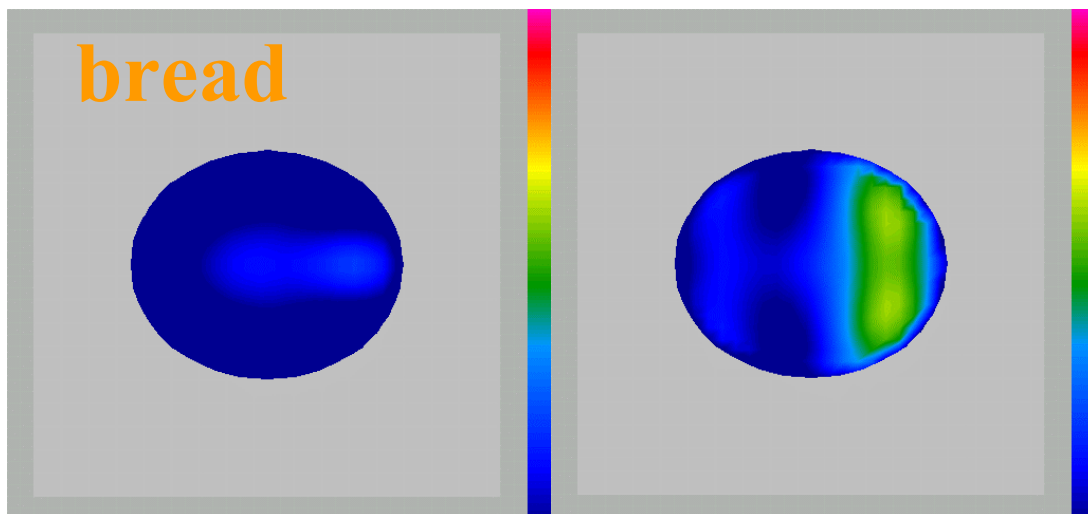


-20 deg.

+20deg.



After 7 thermal iter., each 5 sec.  
Bread - hot spot +20 deg.



# Conclusions

- **A novel FDTD-BHM system performs EM simulation and automatically modifies media parameters as a function of dissipated power.**
- **Parameters of thousands of FDTD cells filled with different media and heated up differently are upgraded in a matter of seconds.**
- **Each consecutive EM steady-state is reached by over an order of magnitude faster by starting from the previous steady-state, rather than from the initial zero EM field.**
- **The system is flexible in handling nearly arbitrary media characteristics, defined by the user in text files, either versus enthalpy or temperature.**

# Planned extensions

- **load rotation**
- **interfaces to heat transfer software**