New Capabilities of FDTD Modelling Software for Microwave Power Applications

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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

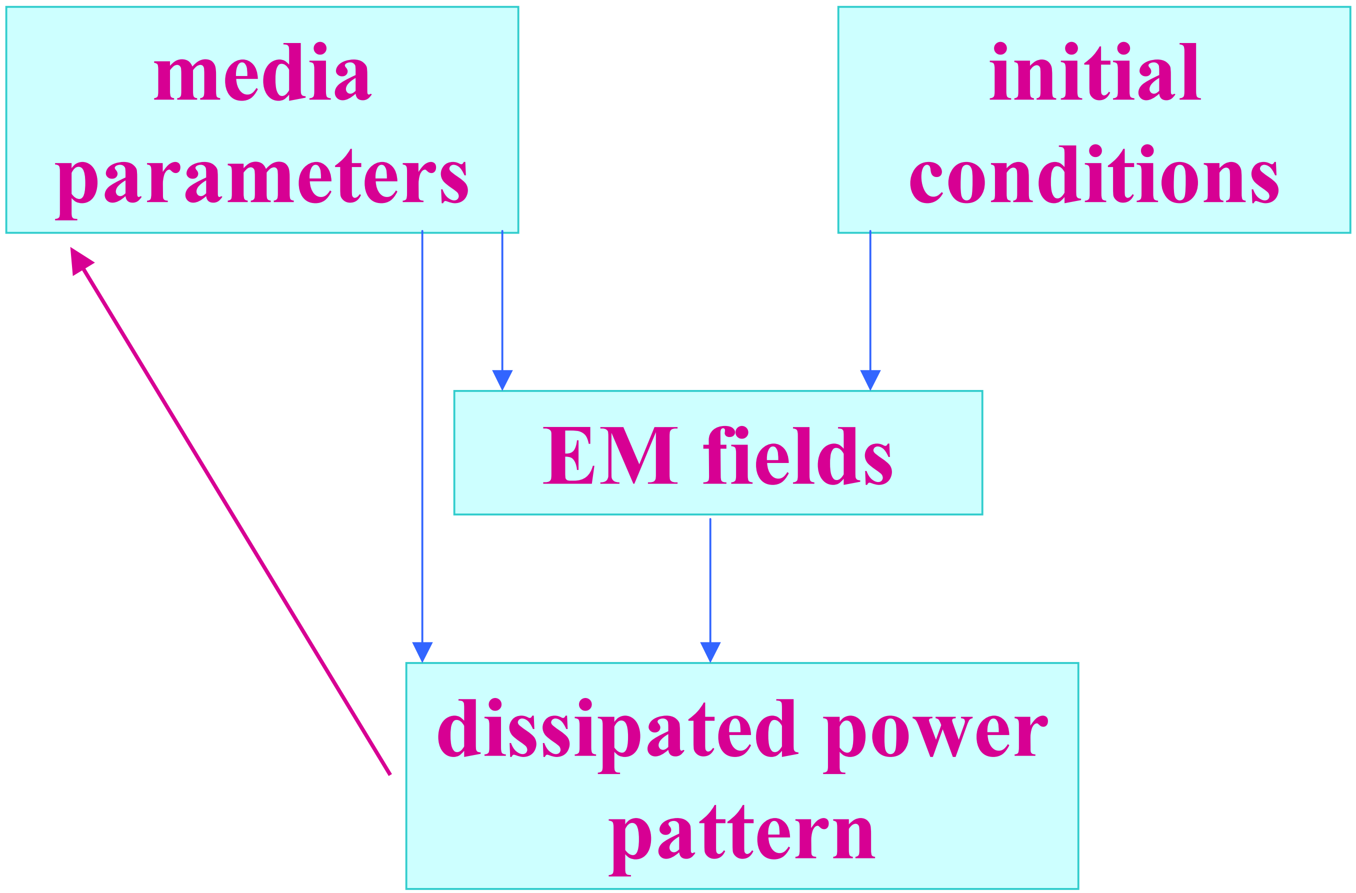
- Adequacy of implemented models & procedures (and their price) for MW heating
- Adequacy of GUI (and its price) for MW heating
- New regimes and features needed for MW heating:

  enthalpy-dependent media parameters,

  load movement,

  heat transfer.

Problem overview



Hints: microwave cycle ~nsec;
change in media params. ~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**

	FEM - direct	FEM – iterative	FDTD
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

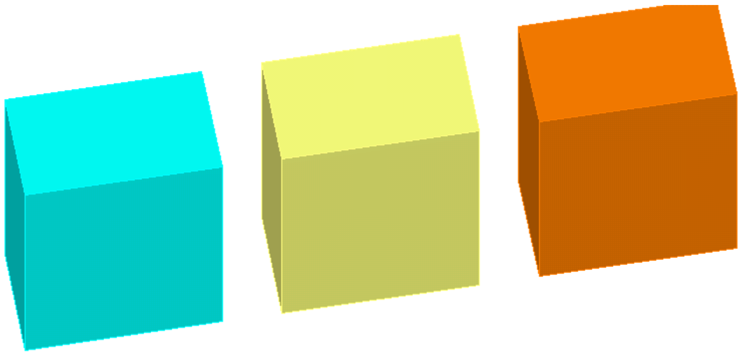
```
#Raw beef draft media
#Measurements & refinements by Per O Risman, Microtrans AB, Sweden
# DATA FROM -20 C to +80 C, dH/dV in J/cm3 NO Specheat column; reversedEnth/Temp
!Temperature    Enthalpy        EPx      EPy      EPz      SIGx     SIGy     SIGz
# Data deg C      J/cm3                             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...

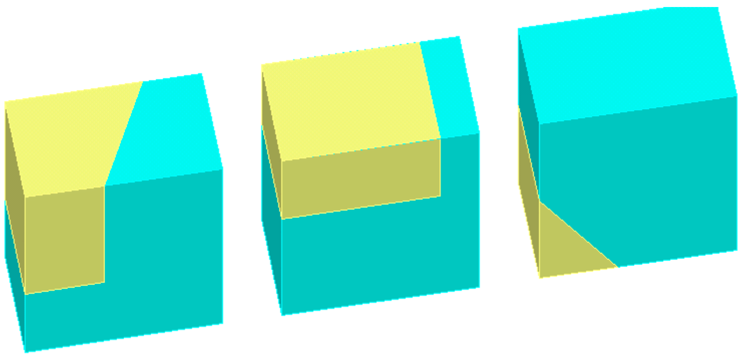
Standard FDTD cells



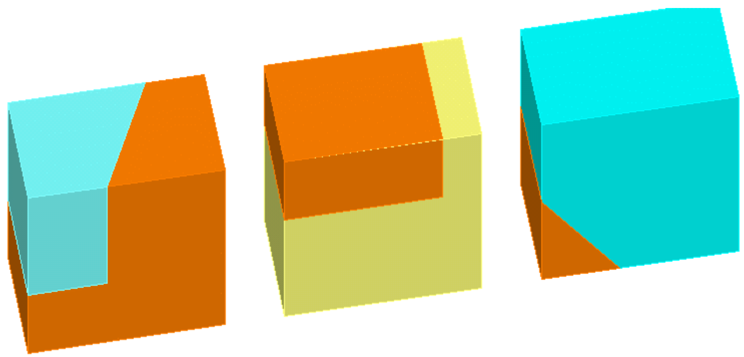
→ "stair-case" FDTD

air dielectric metal

Conformal cells



dielectric media interfaces



metal boundaries

Quick notation & *lcsm* pre-processor

Standard FDTD notation:

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

$$ + [{}_{k,l-0.5,m+0.5}H_x^{n+0.5} - {}_{k,l+0.5,m+0.5}H_x^{n+0.5}](\Delta t/\Delta y)\} \,/({}_{k,l,m+0.5}\varepsilon_z\, \varepsilon_0) $$

prescripts - spatial location; superscripts – time instants;

Δx, Δy, Δz, Δt - discretisation steps in space and time

Our notation:

$$ {}_{k,l,m+0.5}e_z^{n+1} = {}_{k,l,m+0.5}e_z^{n} + [{}_{k+0.5,l,m+0.5}h_y^{n+0.5} - {}_{k-0.5,l,m+0.5}h_y^{n+0.5} $$

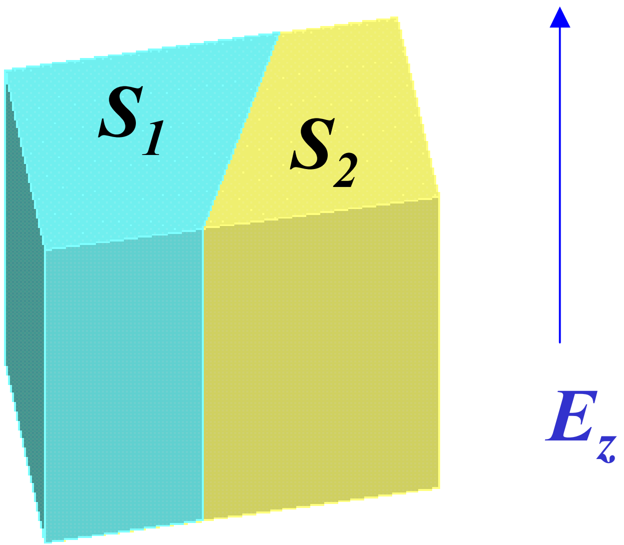
$$ + {}_{k,l-0.5,m+0.5}h_x^{n+0.5} - {}_{k,l+0.5,m+0.5}h_x^{n+0.5}\,] \,/\, {}_{k,l,m+0.5}c_z $$

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

η - free space impedance; c – speed of light

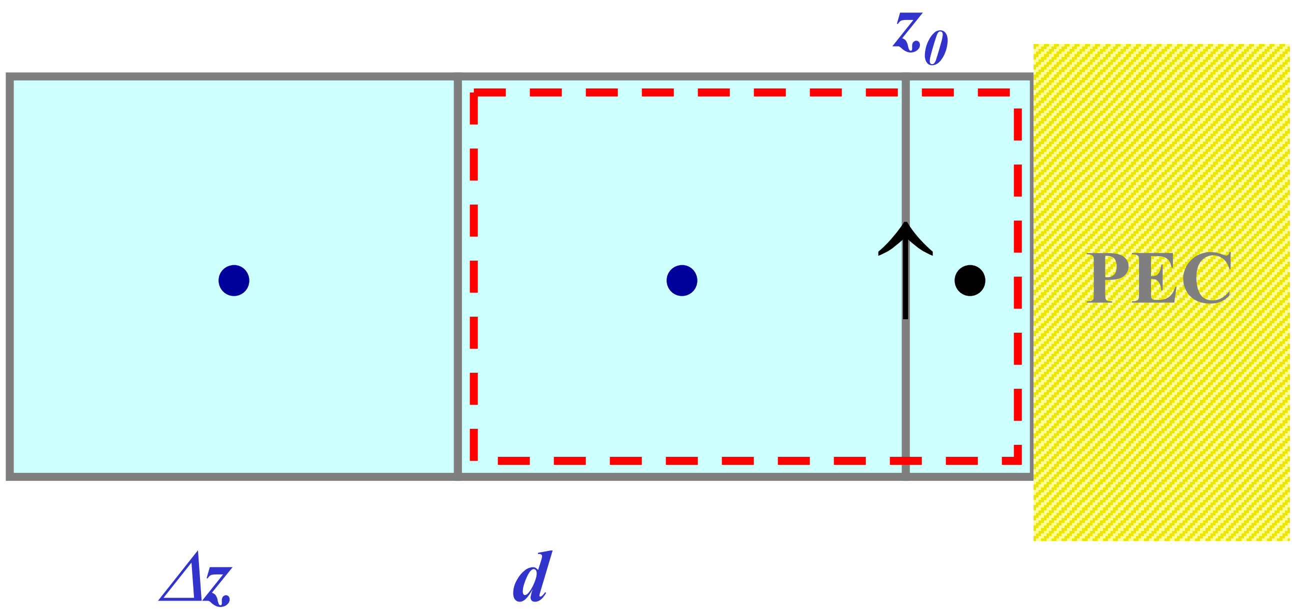
Offset dielectric interfaces

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



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

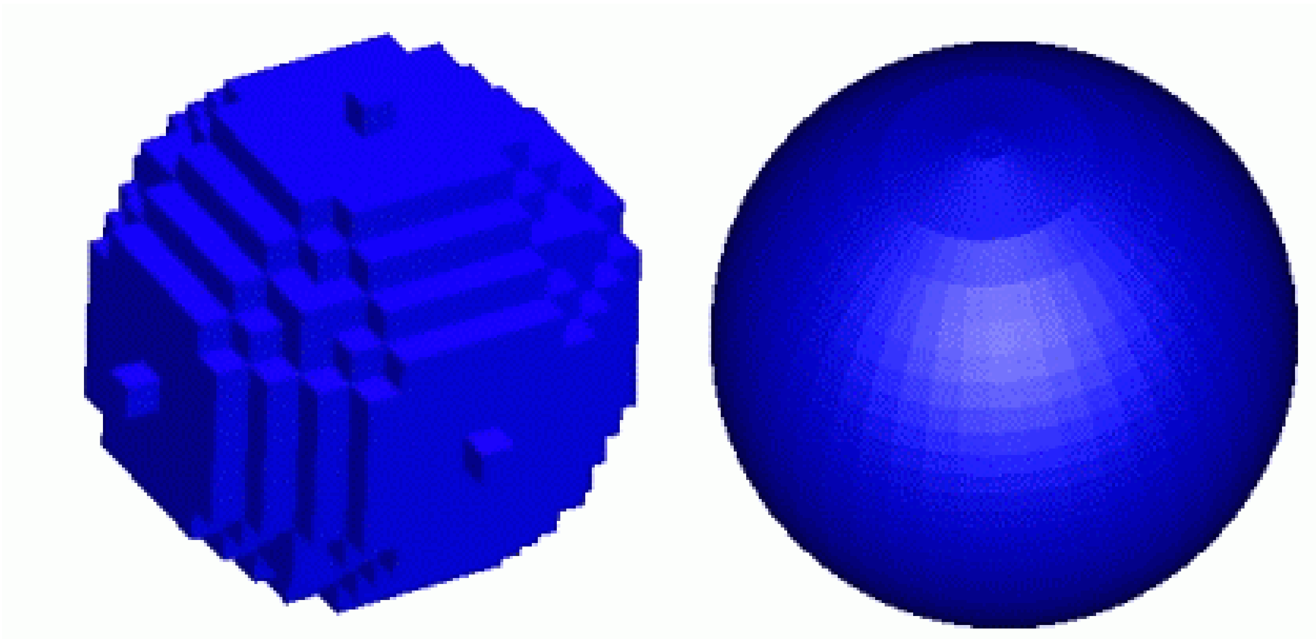
Offset metal boundaries



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

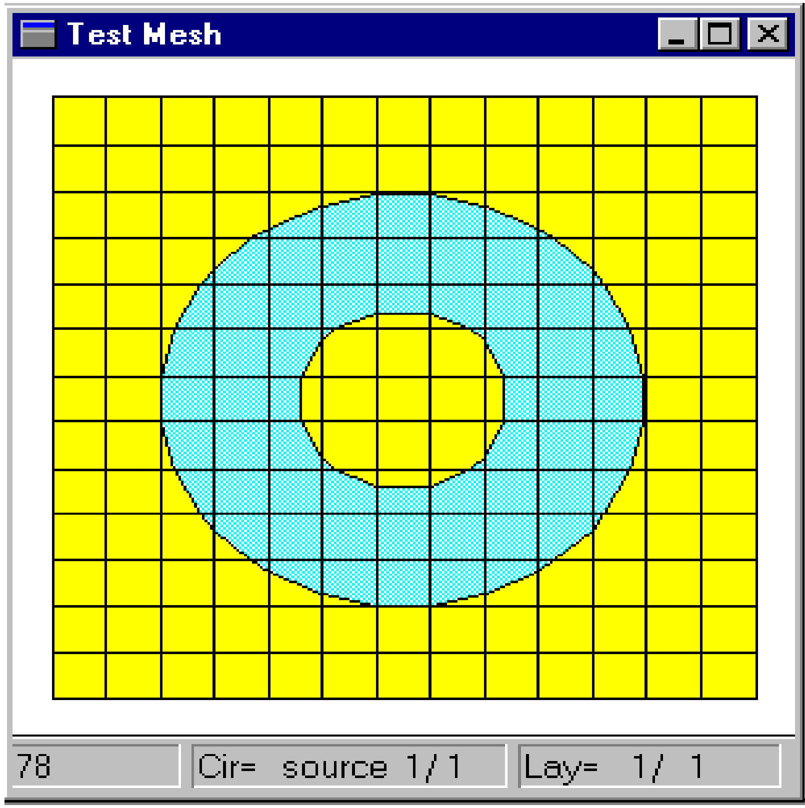
Attention: $\Delta t < a_{min} / (c\sqrt{3})$

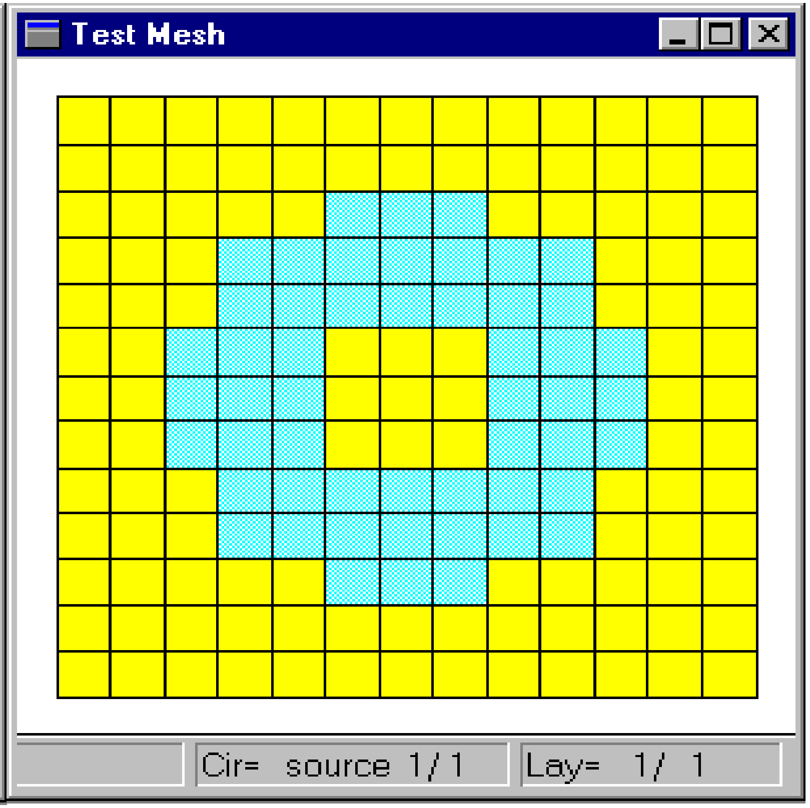
Conformal versus stair-case mesh



e.g.: potato, egg

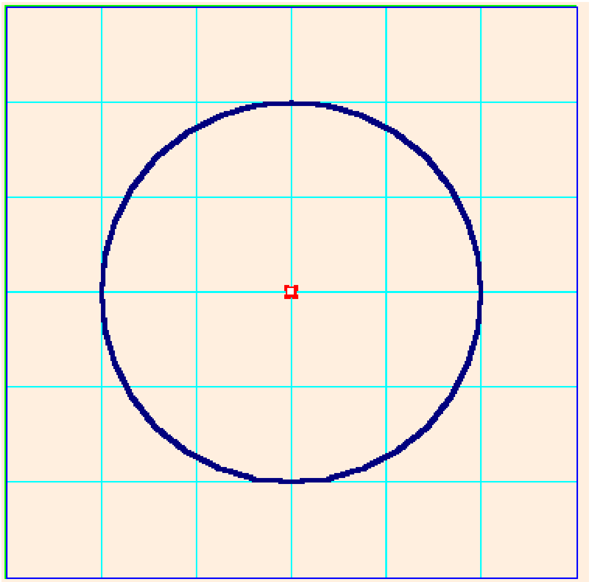
Conformal versus stair-case mesh

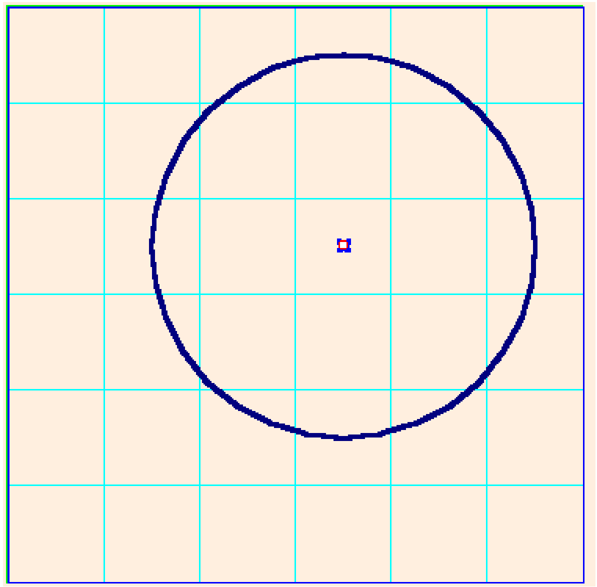


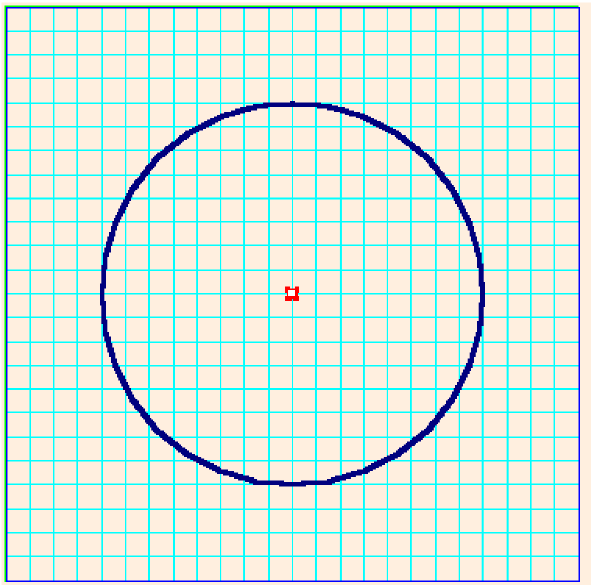


e.g. cross-section through: coaxial line, hot-dog, donut

Meshing a cylindrical object



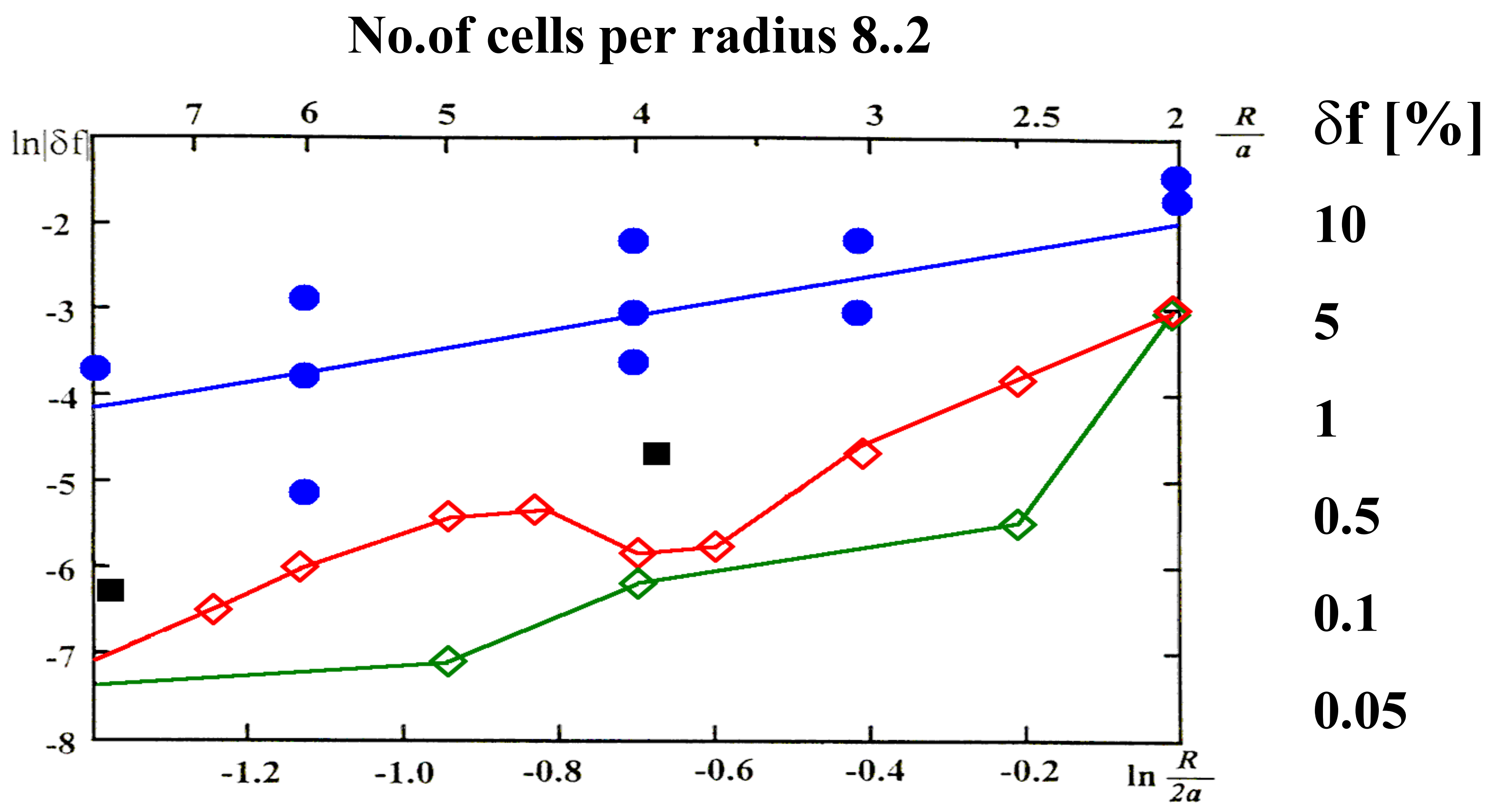




e.g. cross-section through:

- glass plate
- hamburger
- pizza

Analysing a cylindrical resonator

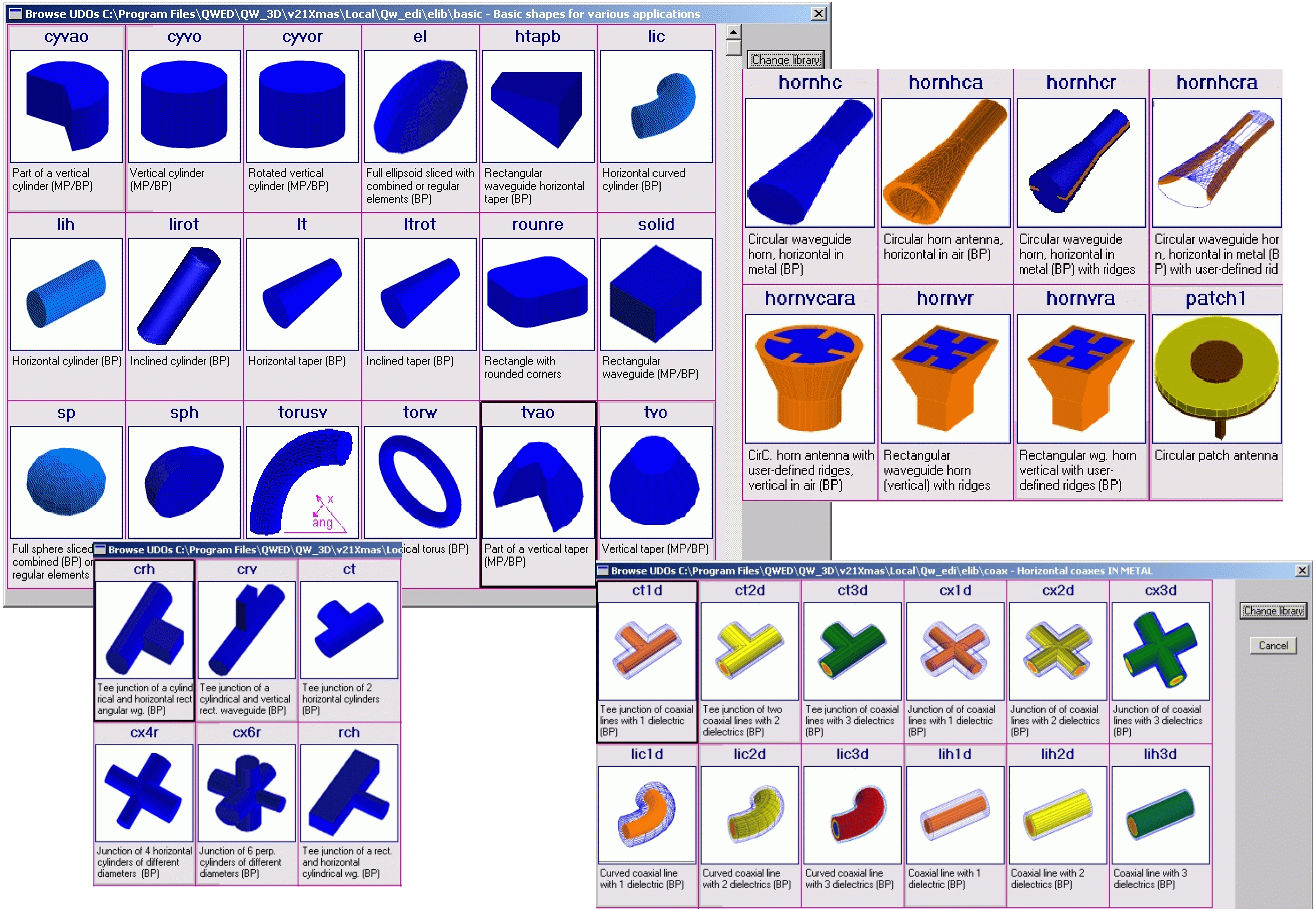


stair-case

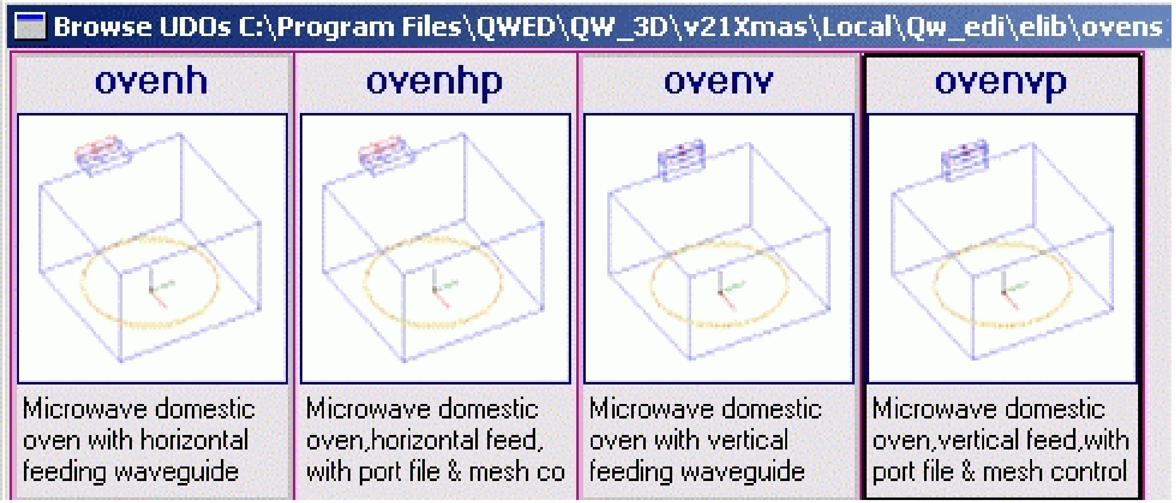
no or simple merging (Railton & Schneider, *MTT Trans.* Jan.1999)

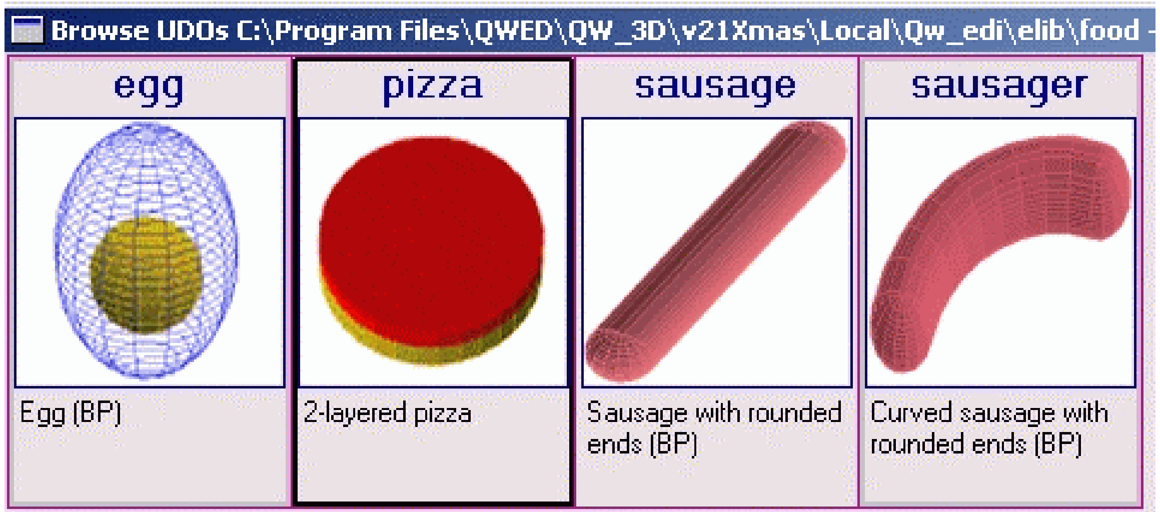
directional cell merging **linearised directional cell merging**

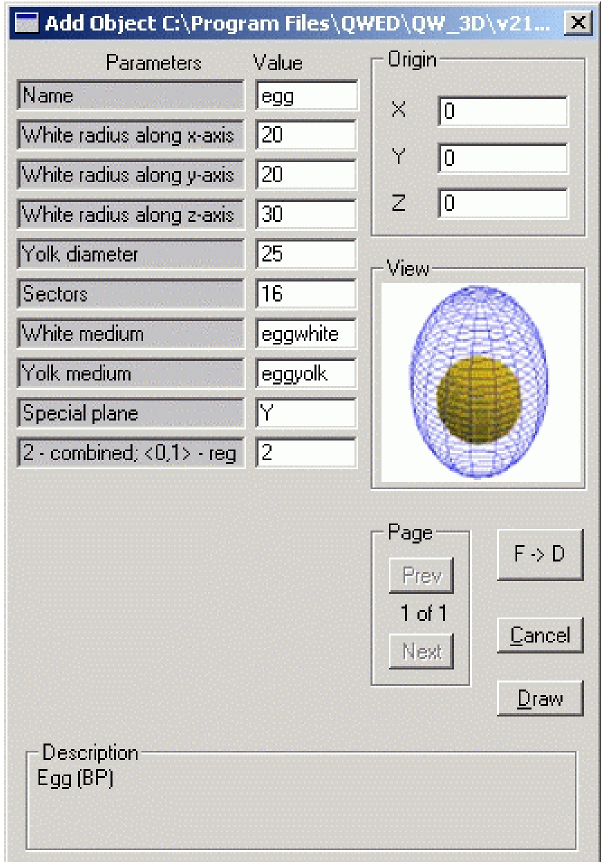
User interface: some basic libraries



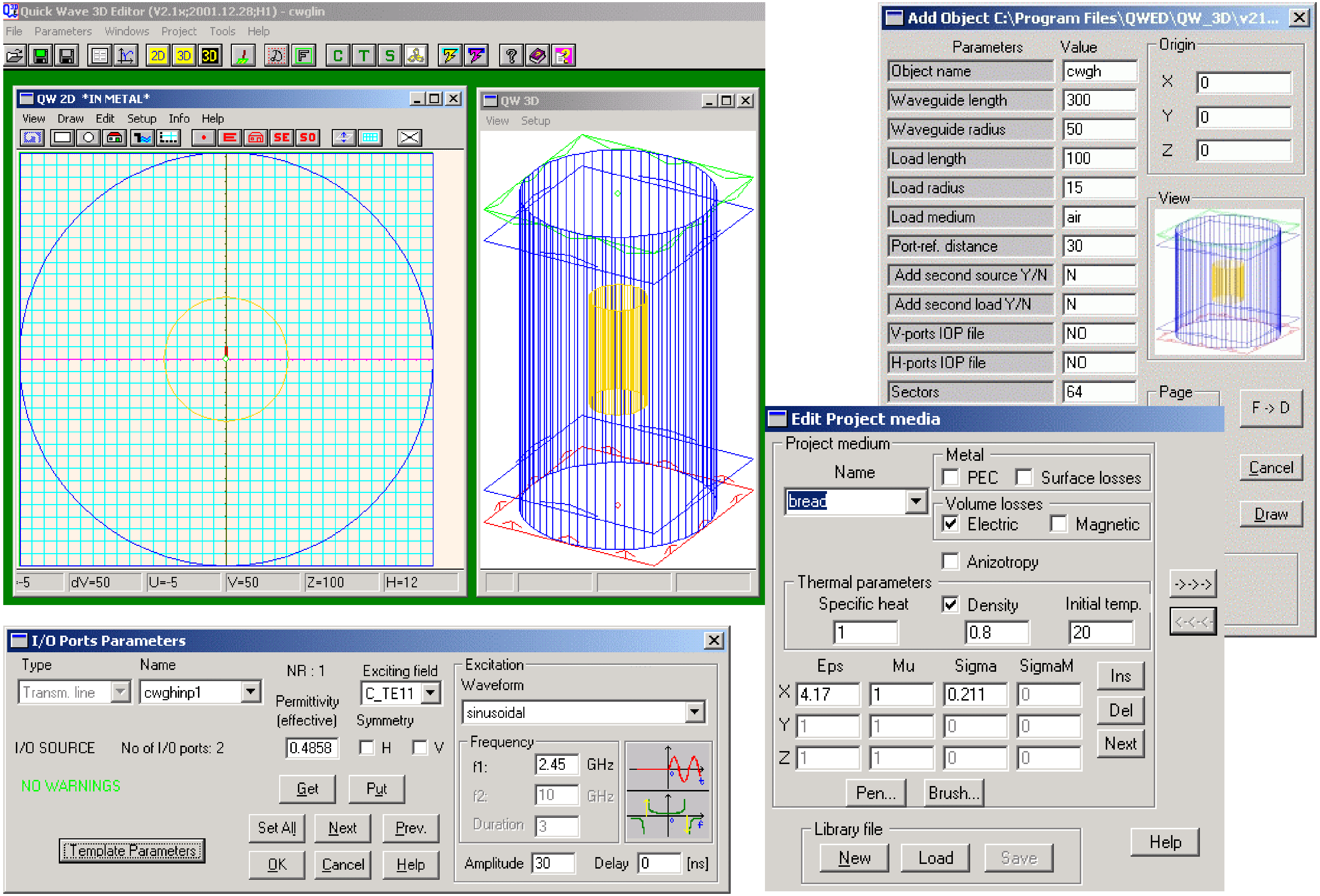
Some specialised libraries





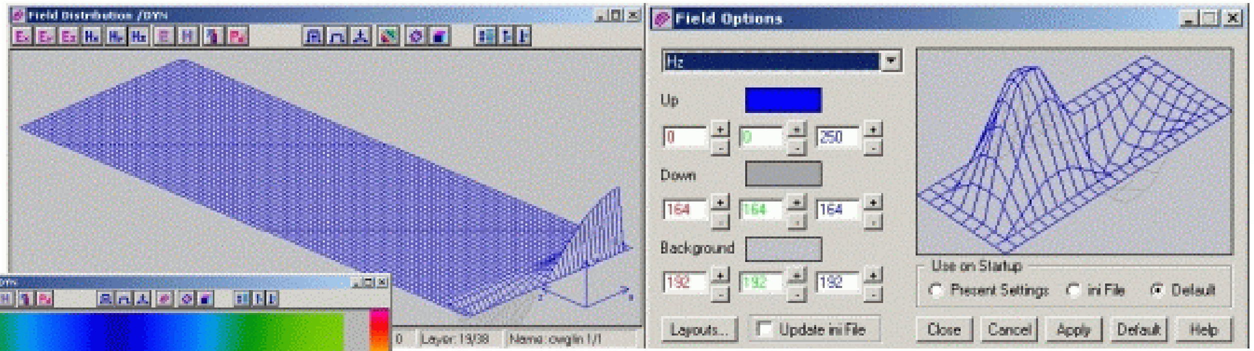


Example 1: heating in circular guide

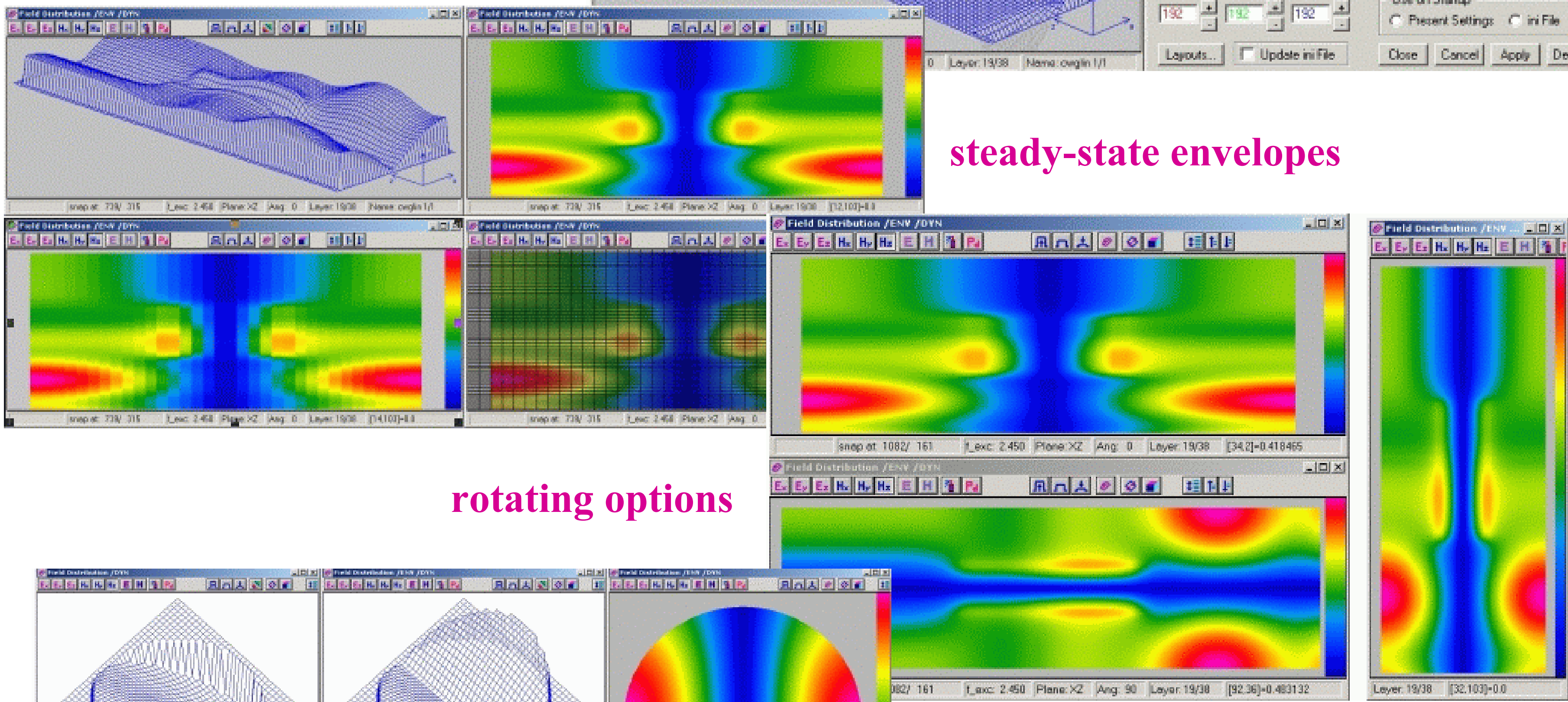


Example 1: longitudinal H-field

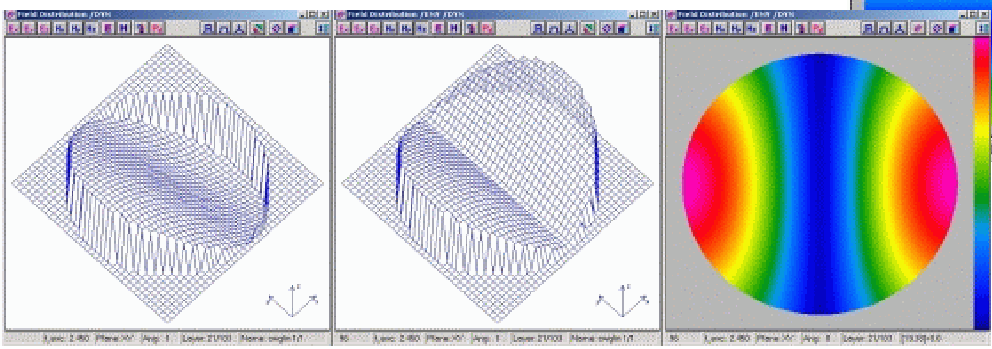
transients & display options



steady-state envelopes



rotating options



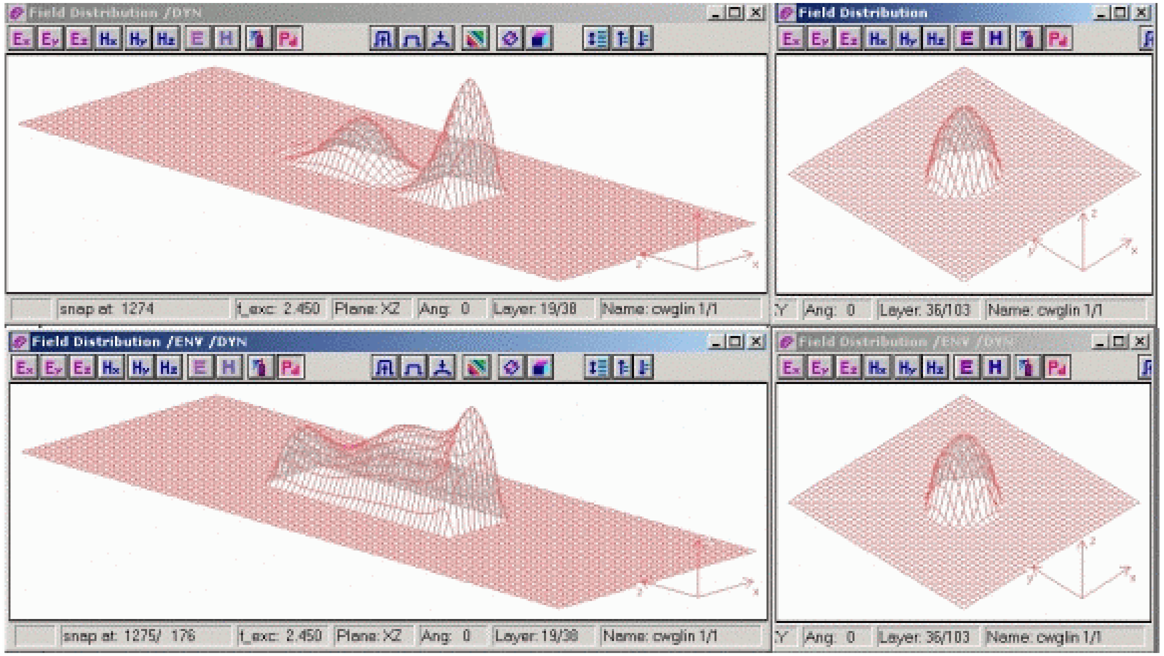
cross-sectional mode pattern

Example 1: heating patterns

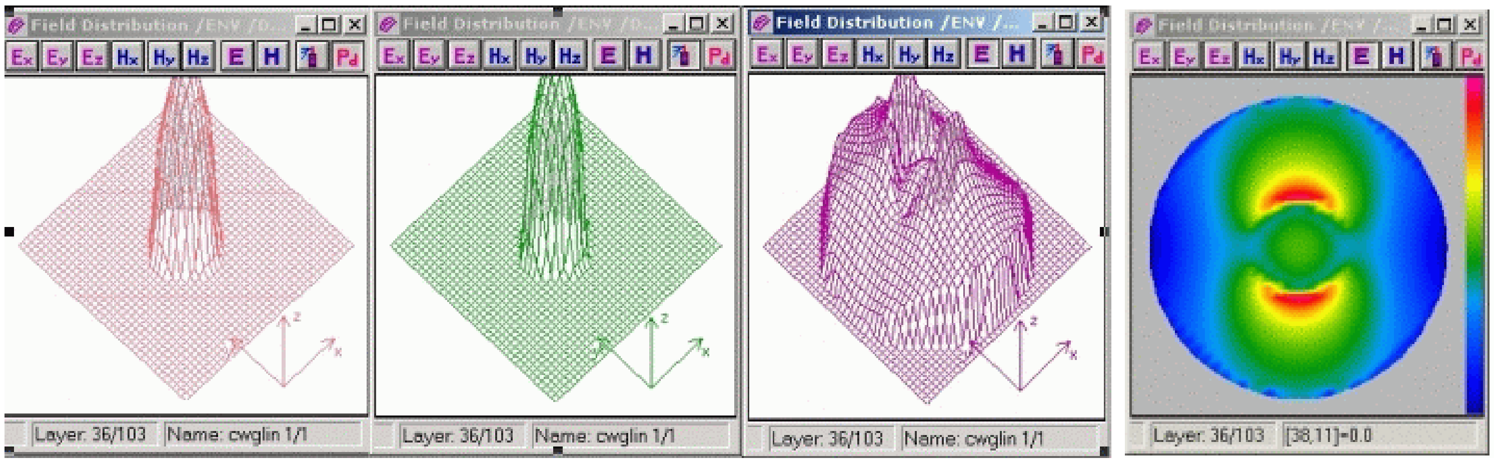
Dissipated power

instantaneous

envelope

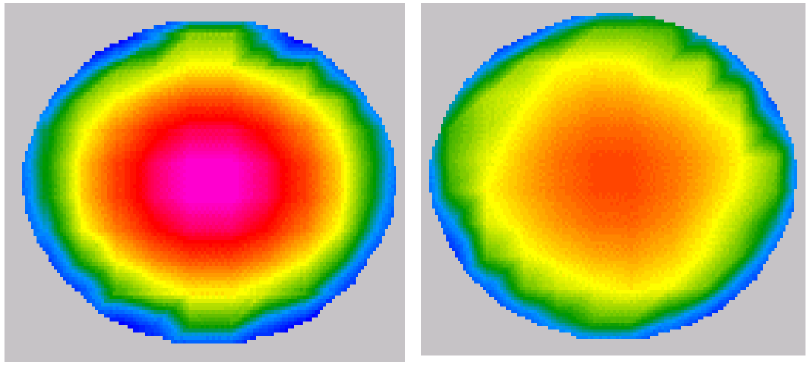


Power **SAR** **total E-field**

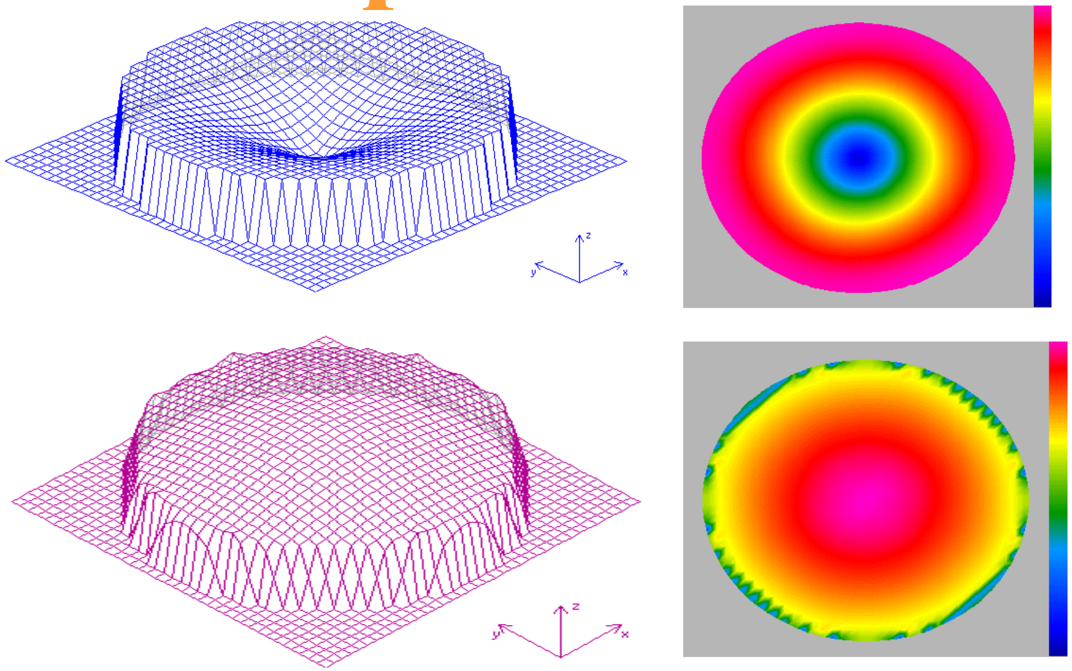


Example 1: circular polarisation

Power envelopes:

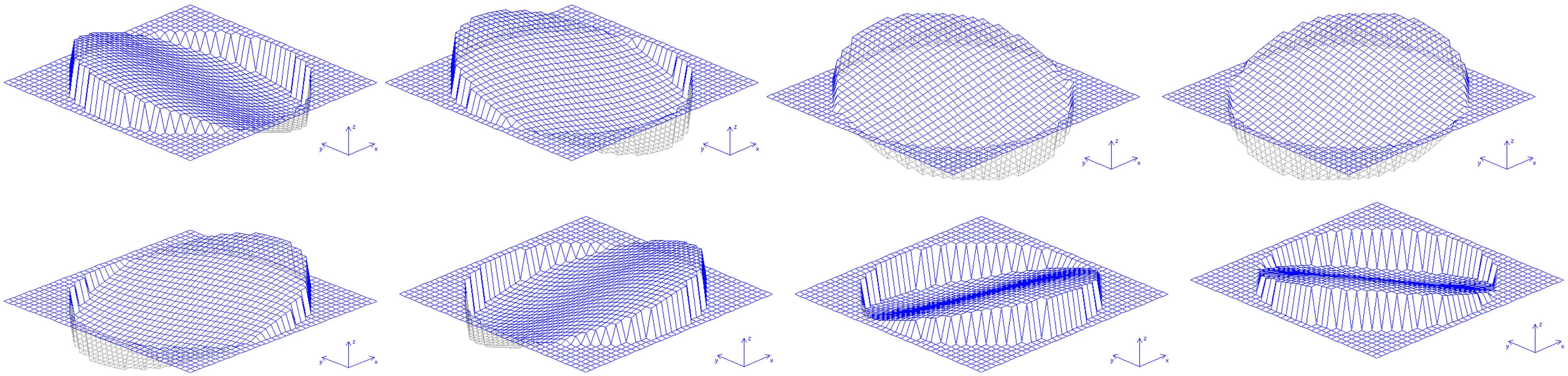


linear **circular**



Envelopes: longitudinal H , total E

Instantaneous H:



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 *lcsm* 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 *lcsm* compilation. For each cell at (x,y,z), read new media parameters from **.pmo*, 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, ε_z and *H* are listed:

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

b) *medium.pmo* exists, ε_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 ε_z is not listed:
default ε_z (as defined in QW-Editor) maintained.

linear interpolation between listed points,
flat extrapolation outside listed range

How to choose $\Delta\tau$

$\rightarrow$ **system stability and rate of convergence**

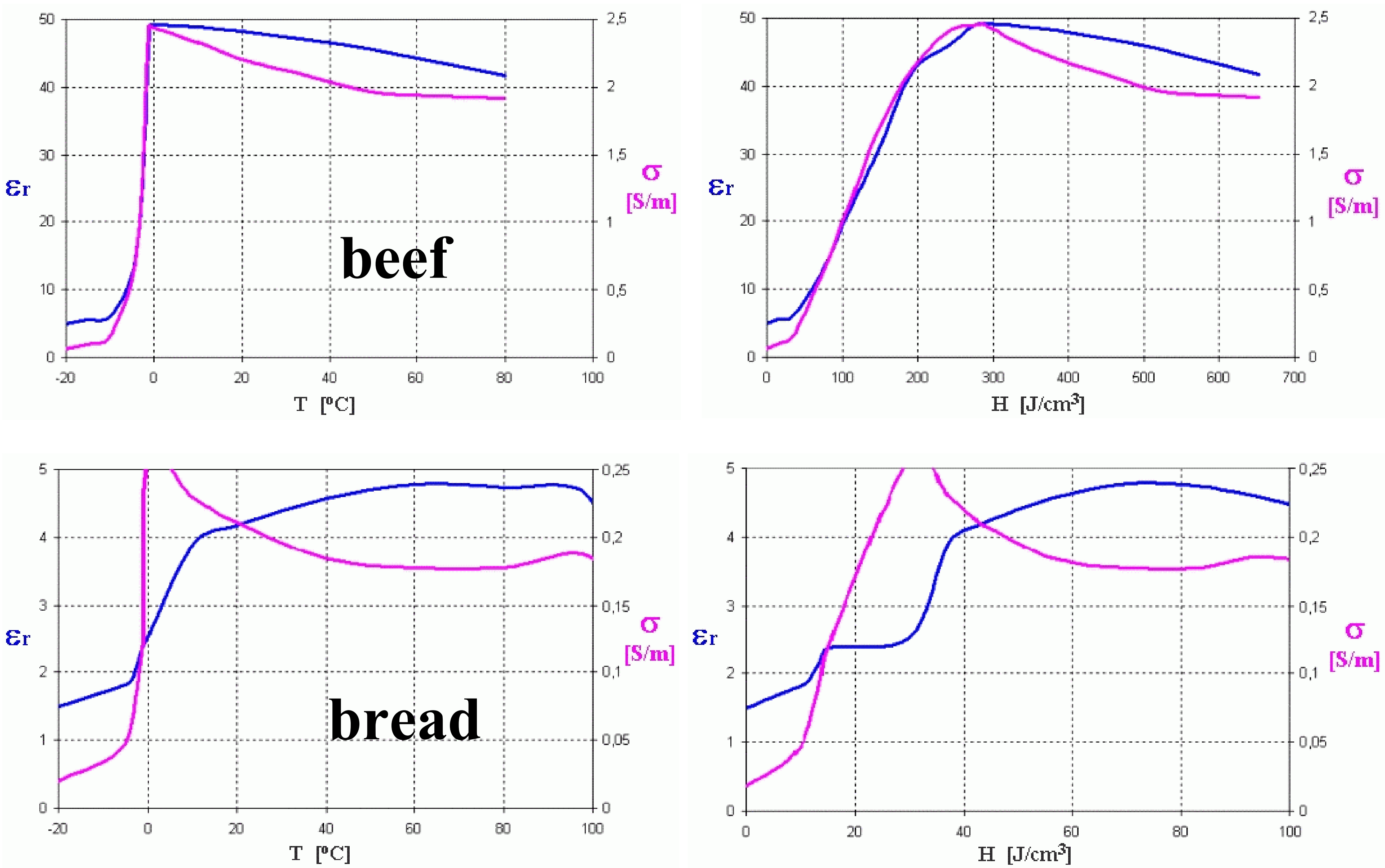
Hint: no scaling involved!

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

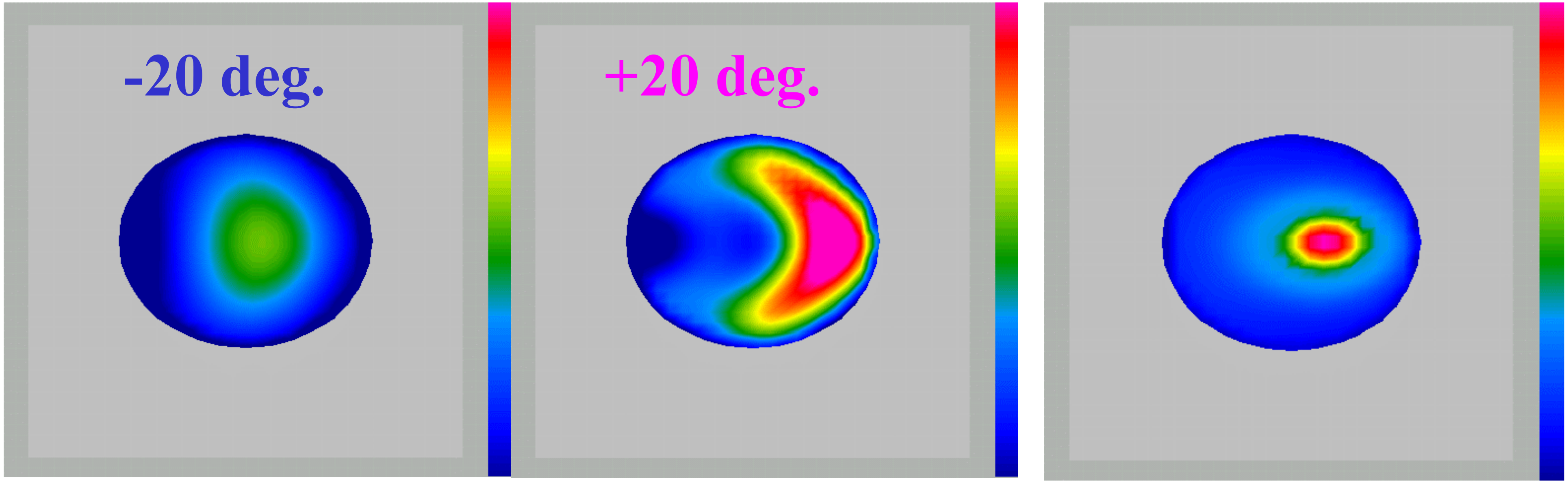
source available power in [W] is set by the user

- **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

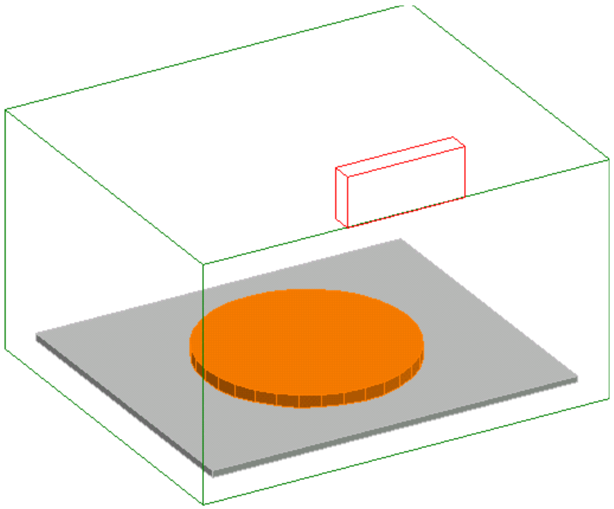


FDTD-BHM result

7 thermal iter., each 2 sec.

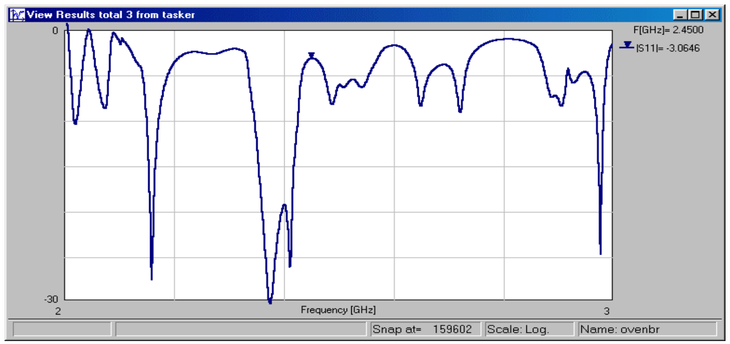
frozen edge -10 deg.

hot spot +33 deg.

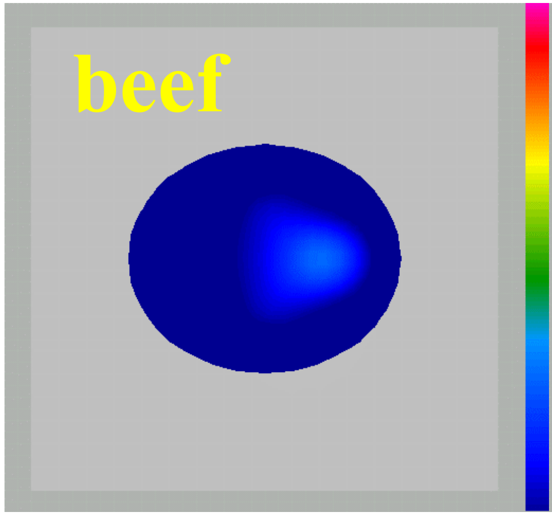


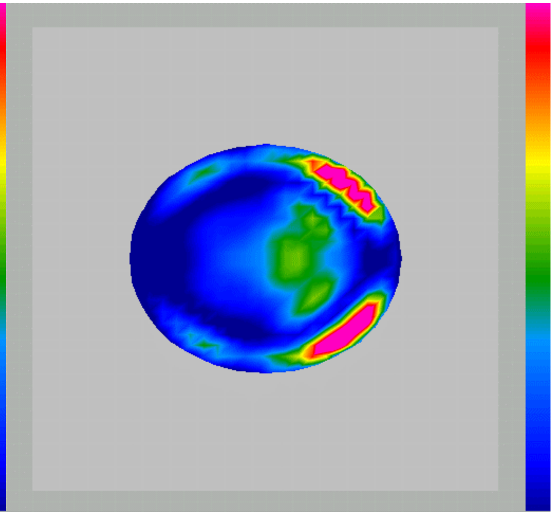
cavity 204x204x228mm,
plate 180x216x6mm
at z=12mm, ε'=6
feed 12x70mm,
source 2.45GHz, 625W,
bread r=60mm, h=6mm

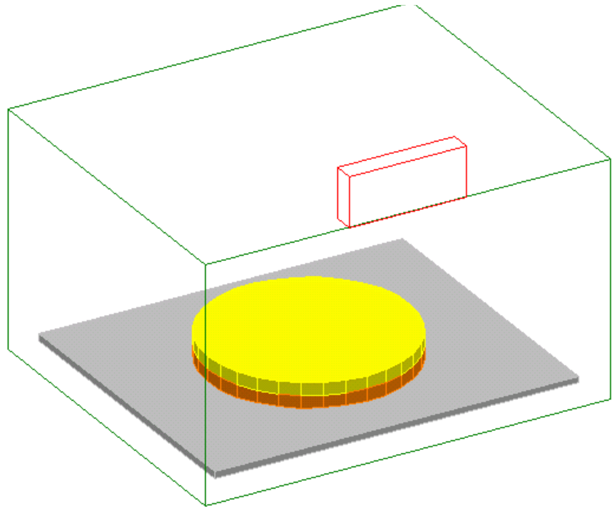
Return loss at +20 deg.



Example 3: beefburger



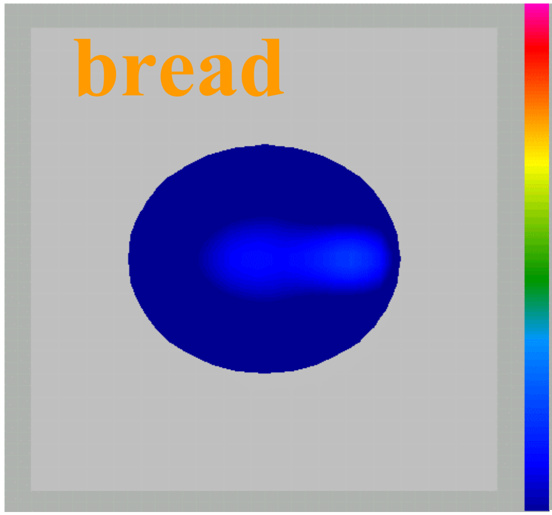


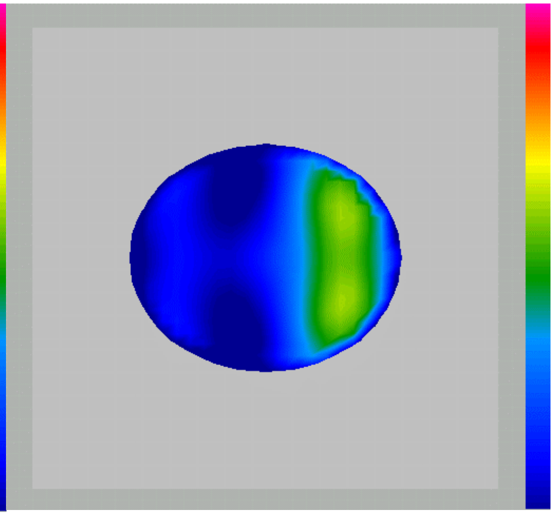


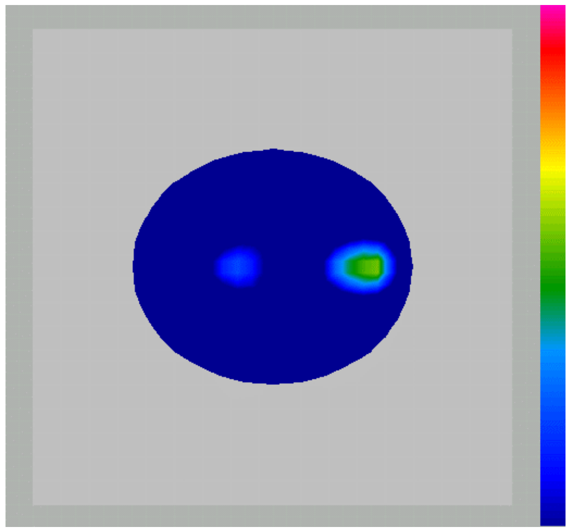
-20 deg.

+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