EMMC Workshop 2019
Industrial Impact of Materials Modelling
8-10 July 2019, Turin - Italy

Why set up a modelling SME when you are student?

- the economic impact of QuickWave software

Dr. Malgorzata Celuch

President & Senior **Scientist**,
QWED Sp. z o.o., Poland

electromagnetic modelling as ***science*** & as ***business***

mceluch@qwed.eu

www.qwed.eu

www.mmama.org

MMAMA

Acknowledgements

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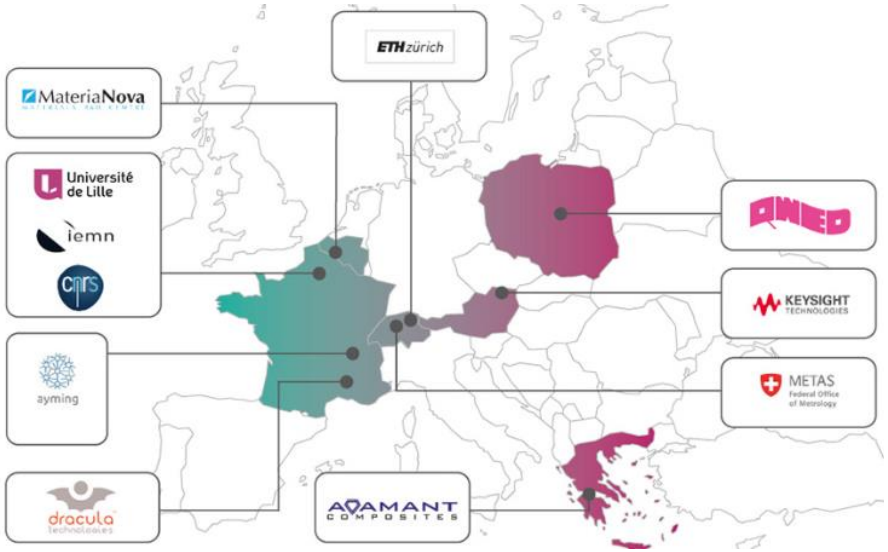
MMAMA n°761036.

(website: www.mmama.eu)



THE EUROPEAN INFORMATION TECHNOLOGY PRIZE *Winner*

Simulations were conducted with QuickWave EM software, developed & commercialised (since 1997) by QWED.

The original designs of QWED resonators for material measurements were from Prof. Jerzy Krupka, e.g.:

J. Krupka, A. P. Gregory, O. C. Rochard, R. N. Clarke, B. Riddle, and J. Baker-Jarvis, "Uncertainty of complex permittivity measurements by split-post dielectric resonator technique", *J. Eur. Ceramic Soc.*, vol. 21, pp. 2673-2676, 2001.

J. Krupka and J. Mazierska, "Contactless measurements of resistivity of semiconductor wafers employing single-post and split-post dielectric-resonator techniques," *IEEE Trans. Instr. Meas.*, vol. 56, no. 5, pp. 1839-1844, Oct. 2007.

Microwave heating scenarios & concepts by Per O. Risman, Microtrans AB & Malardalen University, Sweden.

Outline

- Electromagnetic modelling as science
  - what is EM modelling and how it relates to materials
  - my PhD studies & 3D FDTD "Copernicus version" in 1994-1996
- Electromagnetic modelling as business
  - QuickWave by QWED & economic impact on QWED
  - economic impact on QWED customers & partners
- Modelling workflows in QuickWave that stimulate "transfers of technology"
  - "*near field imaging*" from MW heating
  - multiphysics modelling of MW heating
  - common CAD interfaces
  - sub-cellular models in FDTD (*hints*)
  - "*near field imaging*" in antenna design
  - material data: between simulations & measurements
- User stories.. scattered thoughout the slides

Electromagnetic modelling for microwave technology

Microwaves (MW) – EM waves formally of GHz range – here: modelling from below MHz to hundreds of THz

Electromagnetic (EM) modelling =
= solving Maxwell equations with boundary & initial conditions subject to material constitutive relations

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \qquad \oint_l \vec{E}\,\vec{dl} = -\frac{d}{dt}\iint_S \vec{B}\cdot\vec{n}\,ds$$

$$\nabla \times \vec{H} = \frac{\partial \vec{D}}{\partial t} + \vec{J} \qquad \oint_l \vec{H}\,\vec{dl} = \iint_S \left(\vec{J} + \frac{\partial \vec{D}}{\partial t}\right)\cdot\vec{n}\,ds$$

$$\nabla \cdot \vec{D} = \rho \qquad \oiint_S \vec{D}\cdot\vec{n}\,ds = \iiint_V \rho\,dv$$

$$\nabla \cdot \vec{B} = 0 \qquad \oiint_S \vec{B}\cdot\vec{n}\,ds = 0$$

$$\nabla \cdot \vec{J} = -\frac{\partial \rho}{\partial t} \qquad \oiint_S \vec{J}\cdot\vec{n}\,ds = -\iiint_V \frac{\partial \rho}{\partial t}\,dv$$

general: $\vec{D}, \vec{B}, \vec{J} = F(\vec{E}, \vec{H})$

typical: $\vec{D} = \underline{\underline{\varepsilon}} \cdot \vec{E}$

$\vec{B} = \underline{\underline{\mu}} \cdot \vec{H}$

$\vec{J} = \underline{\underline{\sigma}} \cdot \vec{E}$

Two perspectives of EM modelling (continuum, physics-based)	
EM wave propagation in space (also in-between boundaries)	**EM field interaction with materials**
1990s: radars, radio & TV, electronic circuits	**MW ovens**
today: telecommunications (5G), RFID (ski-pass), IoT (wearable sensors)	**biomedical (diagnostics – breast cancer, treatment – hyperthermia) MW chemistry, wood drying, plastics curing, rock comminution**

"Modelling" for microwave technology: my *personal* view of history

Until 1980s:

- heuristic equations (experimental models; today: data based?)
- lumped circuit approximations (0-dimensional: dimensions<< wavelength)
- 1D approximations (transmission lines, long lines, telegraphists equations, Smith chart)

In 1980-1990s:

- academic research on solving Maxwell eqs.

dimensionality in space	fields in space	fields in time
2D	modal expansions (method of moment, mode matching...)	monochromatic (frequency-domain approach)
3D	discretisation (FEM, FD, FV, TLM, SpN,..)	arbitrary (time-domain approach)

- commercial software packages implemented in industry

Engineers question in 1990s: will EM software help me?

Engineers question today: can I trust EM software (to fully replace hardware prototyping)?

FDTD modelling at the Warsaw University of Technology in 1980-1990s

W.K.Gwarek, "Analysis of an arbitrarily-shaped planar circuit - a time-domain approach", **invited paper**, *IEEE Trans. Microwave Theory Tech.*, vol.33, No.10, Oct.1985.
W.Gwarek, "Computer-aided analysis of arbitrarily-shaped coaxial discontinuities", *IEEE Trans. Microwave Theory Tech.*, vol.36, No.2, Feb.1988.
→ QuickWave 2D launched onto the market by ArguMens GmbH

M.Celuch-Marcysiak & W.Gwarek, "Formal equivalence and efficiency comparison of the FD-TD, TLM and SN methods in application to microwave CAD programs", *Proc. 21st European Microwave Conf.*, Stuttgart, Sept. 1991.
→ FDTD and TLM and SN are formally equivalent but FDTD is computationally more efficient (and opens way to conformal modelling)

PUBLICATIONS IN ENDLESS REVIEWS → DECISION TO PROVE OUR POINT ON THE MARKET
EC SUPPORT via COPERNICUS PROJECT 1994-1996 INTERRUPTED...

BUSINESS BORN OUT OF OBSTACLES?..

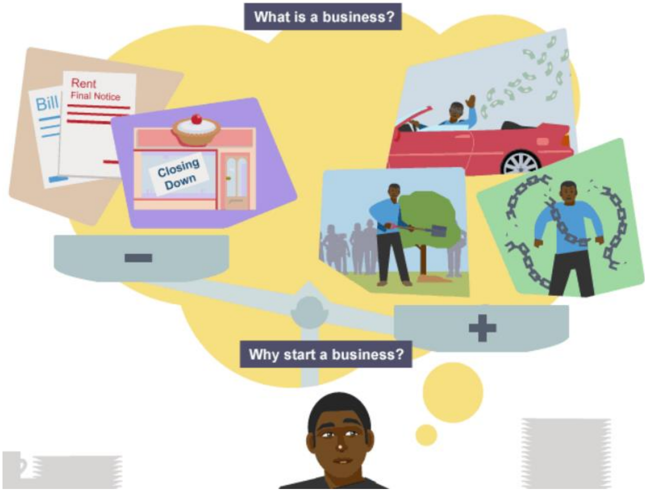
M.Celuch-Marcysiak, "Time-domain approach to microwave circuit modeling: a view of general relations between TLM and FDTD", **invited paper**, *Intl. Journal of Microwave and Millimeter-Wave Computer Aided Engineering*, vol.6, No.1, 1996.
M.Celuch-Marcysiak, W.K.Gwarek, "On the nature of solutions produced by finite difference schemes in time domain", **invited paper**, *Int.Journal of Numerical Modelling*, vol.12, No. 1-2, Jan.-Apr.1999.
M.Celuch-Marcysiak & W.K.Gwarek, "Generalized TLM algorithms with controlled stability margin and their equivalence with finite-difference formulations for **modified** grids", *IEEE Trans. Microwave Theory Tech.*, vol. MTT-43, No.9, Sep.1995.
→ TLM can be made as good as FDTD

International research context:
K.S.Yee, "Numerical solution of initial boundary-value problems involving Maxwell's equations in isotropic media", *IEEE Trans.Ant.Prop.*, vol.14, No.5, 1966.
A.Taflove, M.E.Bodwin, "Numerical solution of steday state electromagnetic scattering problems using the time dependent Maxwell's equations", *IEEE Trans. Microwave Theory Tech.*, vol.33, No.10, Oct.1985.
A.Taflove, S.Hagness, (with chapters co-authored by M.Celuch & W.Gwarek) "Computational Electrodynamics - The Finite-Difference Time-Domain Method", 3rd Edition, Artech House, Boston-London, 2005.

Why set up a business when you are a PhD student...

Why set up a business? Online at (as of 27 June 2019): https://www.bbc.com/bitesize/guides/zc3gkqt/revision/1

"Setting up a business involves **risks** and **reward**.
Profit is the **reward** for risk-taking.
Losses are the **penalty** of business failure."



Why set up a business (expected award)? (*none in my case...*)

- making a profit
- safisfaction of being independent
- satisfaction of being able to make a difference (e.g. charity)
- ...

My reward (expected & achieved):
satisfaction of being able to prove my research concept
with unexpected "penalty" being... responsibility!

How set up a business?

"An entrepreneur knows that setting up in business is a risk.
They need a robust business plan detailing market research
and competitor analysis and a good knowledge of the market."

I knew or did little of the above...

"Marketing" of QuickWave was all based on need & trust

1. People trusted us based on our documented research results
2. We trusted our own choices & solutions, and were not afraid of challenges:

> *"During this early period QWED had a client (..), developing filters. They had problems with the differences between the experimental and modelling results. Andrzej W. worked on that and after some time found out that the discrepancy was a 1 or 2 µm wide air or oxide gap between two connecting metal parts. He solved the whole thing very impressively, and that would not have been possible with a FEM method I think. "*

3. We were not afraid to develop new functionalities from scratch
(e.g. ferrite model for crisp plates was provided to a customer in 2 weeks from the first enquiry)
4. Our clients were becoming our marketing force

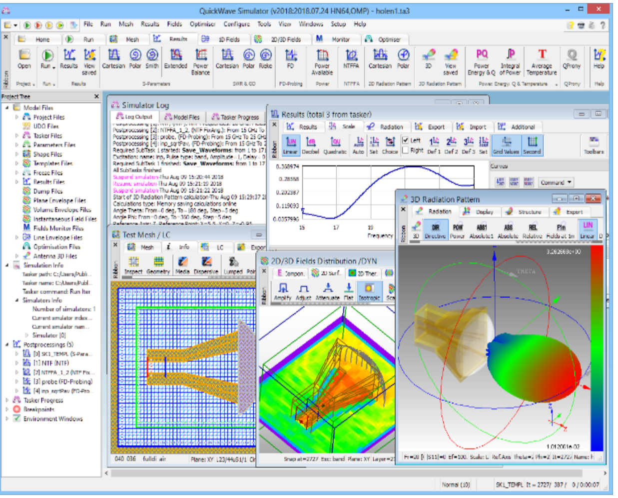
4. We also trusted what our **expert** users told us about the market:

> *"With my knowletedge of the weaknesses of FEM anf FDTD I was encouraged to arrange a competition, in 1999 I think. This was between four vendors, two FDTD and two FEM (..). One of the scenarios was a rectangular waveguide very near cut-off, which was the most interesting of the examples. – Only QWED solved that correctly, and I remember the US expert of an US vendor calling me in the middle of the night over the "impossibility to solve the damned problem". (..) I presented to poutcome of the test at an IMPI symposium. That evidently resulted in QWED getting some new clients."*

..and we **underestimated** that the popular market prefers "easy" to "accurate"...
..and I **underestimated** the burden of responsibility (towards users & employees)

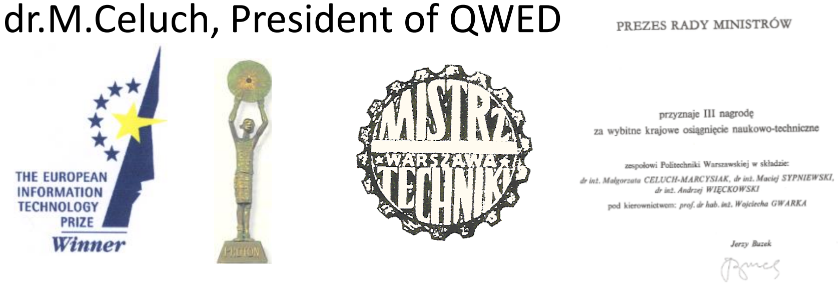
Polish high-tech SME - 22 years on the world's market

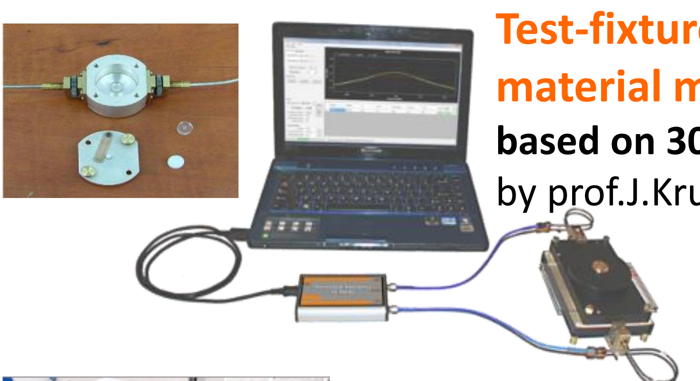
Business branches *presented annually at IEEE IMS Show*



Electromagnetic simulation & design software, 3D & BOR 2D tools

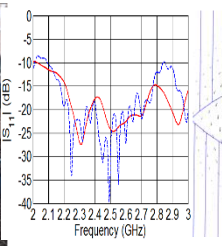
based on 300+ publications by:
prof.W.Gwarek, IEEE Fellow, DML, Pioneer Award
dr.M.Celuch, President of QWED

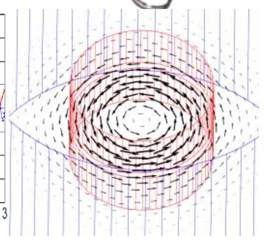




Test-fixtures for precise material measurements

based on 300+ publications
by prof.J.Krupka, IEEE Fellow





Consultancy & design services based on EM expertise & tools

team of 10+engineers, 4 PhDs, 2 Profs
key areas: MW power appliances, customised resonators, antennas &feeds

R&D projects

FP6 SOCOT – development and validation of an optimal methodology for overlay control in semiconductor industry, for the 32 nm technology node and beyond.

FP6 CHISMACOMB – development, modelling, and applications of chiral materials → EM validation of mixing rules

Eureka E! 2602 MICRODEFROST MODEL – innovative software-based product development tool for simulating and optimising heating and defrosting processes in microwave ovens

FP7 HIRF SE (High Intensity Radiated Field Synthetic Environment) - numerical modelling framework for aeronautic industry

Eureka FOODWASTE – developing new microwave treatment system for high water content waste

ERA-NET MNT NACOPAN – applications and modelling of nano-conductive polymer composites

NGAM2 – designing an industrial device for thermal bonding of bituminous surfaces with the aid of microwave heating

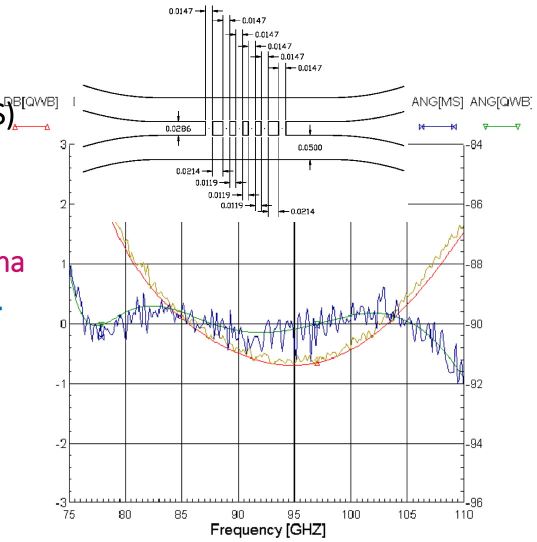
MMAMA (Microwave Microscopy for Advanced and Efficient Materials Analysis and Production) – accelerating the development of high efficiency solar cells through application and enhancement of material measurement techniques

Electromagnetic modelling and design – antennas & feed systems

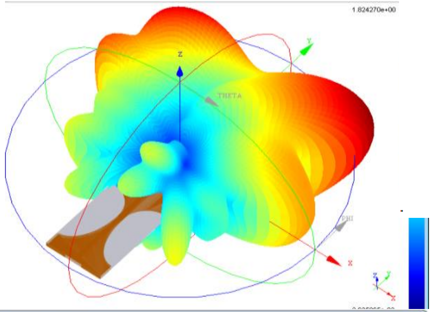
QuickWave-3D: world's recognised 3D EM simulation tool

Space research:
NASA related laboratories:
National Radio Astronomy Observatory (VA US),
Jet Propulsion Laboratory (CA US)
Universities:
CALTECH (US), Chalmers (S), etc.

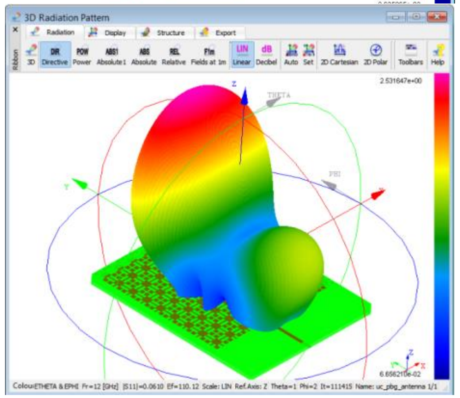
Antenna feed systems designed by NRAO



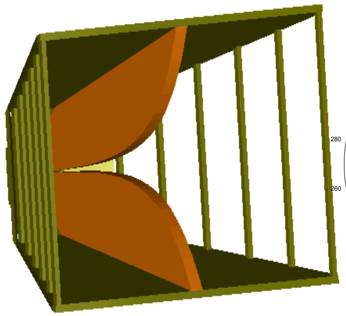
QuickWave 3D results at NRAO, see: ALMA Memos 381, 343, 325, 278.

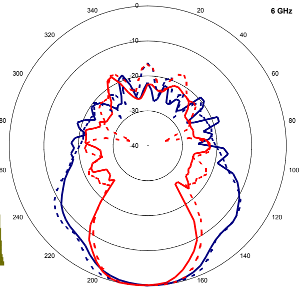


Balanced antipodal Vivaldi antenna & 3D radiation pattern at 10 GHz.



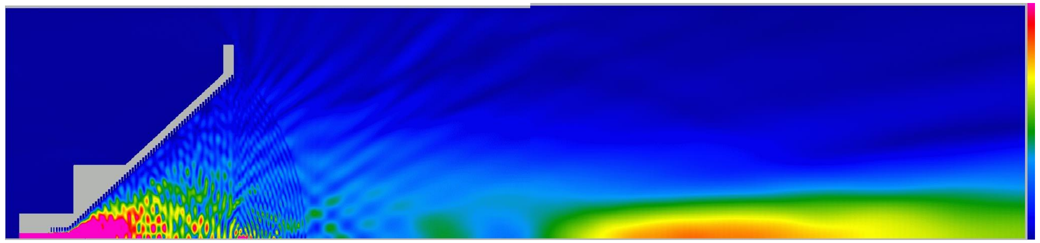
Aperture-coupled patch antenna on uniplanar photonic bandgap substrate & its radiation pattern at 12 GHz.



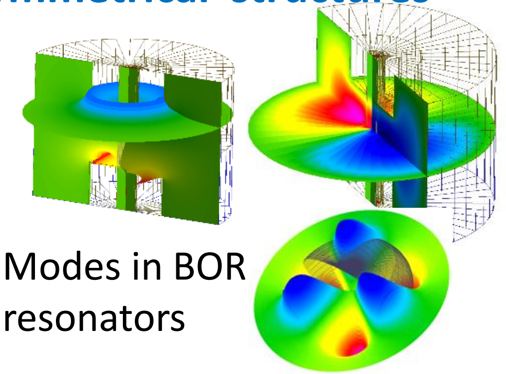


Pyramidal horn antenna for military surveillance measured (courtesy prof.B.Stec) & simulated patterns

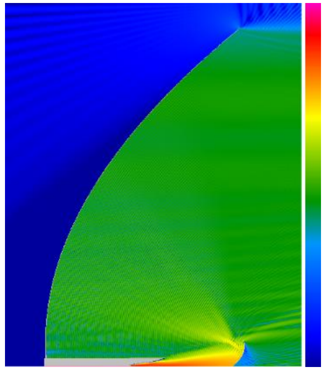
QuickWave BOR: unique on the market & ultrafast tool for axisymmetrical structures



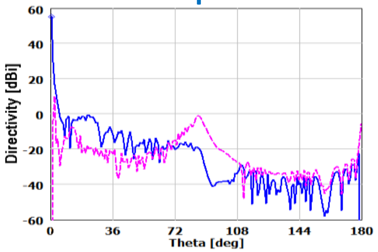
Antennas as large as 2600 λ in diametre on moderate PC

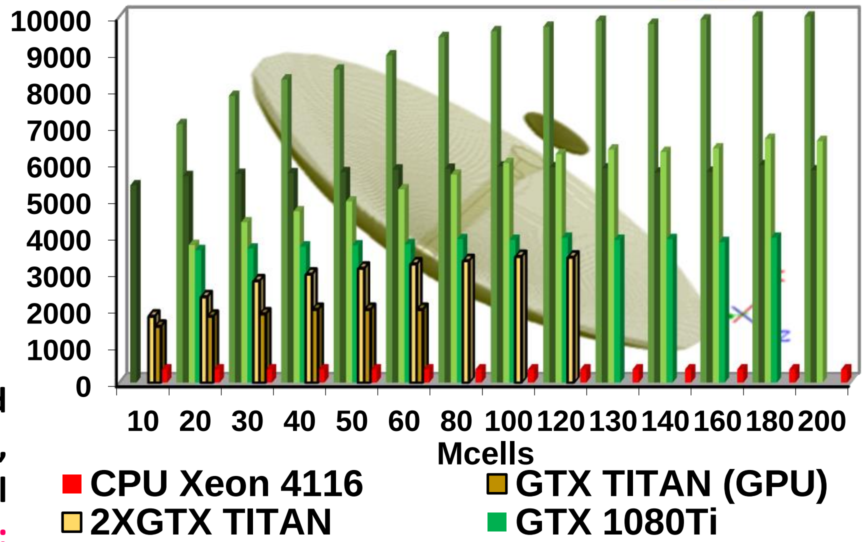


Modes in BOR resonators



Insight into EM near-field helps explain causes of undesired performance





QuickWave is optimised for speed plotted in (Mcells/sec), runs on professional & low-cost video cards:

Pioneering background:
W.Gwarek, *IEEE Trans. MTT*: vol.33 Oct.1985; vol.36 Feb.& Apr. 1988.

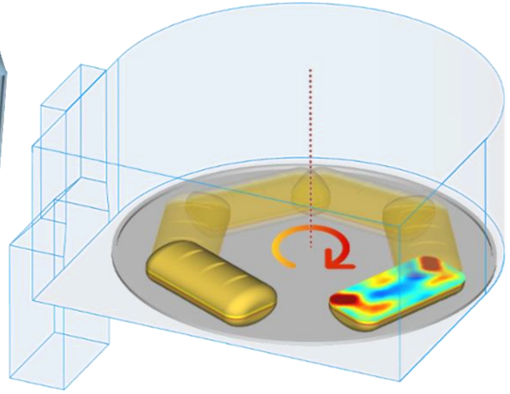
Key developments:
M.Celuch & W.Gwarek, *IEEE Trans. MTT*, vol.43 Sep.1995, vol.41 May1993, vol.45 May1997, vol.51 Aug.2003; *EuMC* 1991-1997; *IEEE IMS* 2001-2004.

Reviews: *IEEE Microwave Mag.*, Dec.2008 & Apr.2010; *IJMPEE* vol.41 2007.

Electromagnetic consulting & design – high MW power applications

Modelling of MW heating effects in domestic oven

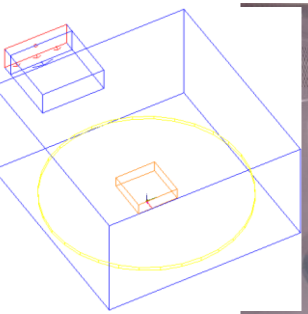
Full-wave EM simulation & heat transfer & load dynamics
Load rotation & arbitrary movement during heating
Source frequency tuning – regime for solid state sources
Temperature dependence of material parameters

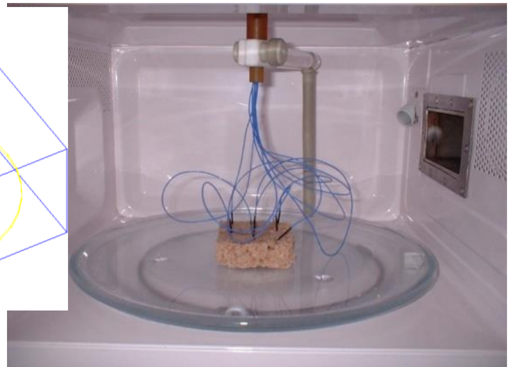


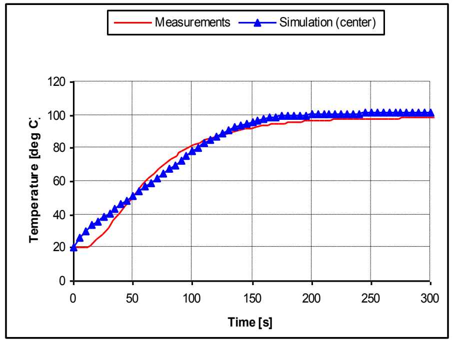
Whirlpool Max oven

Considered by M.Celuch & P.Kopyt in eds. W. Lorence and P. S. Pesheck, *Development of packaging and products for use in microwave ovens*, 1st edition Woodhouse CRC Press 2009, 2nd Ed. Elsevier in print.

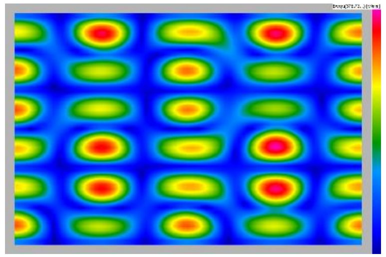
QuickWave modelling of heating confirmed by real-life experiments – joint work of QWED and WUT in Eureka E!2602 project



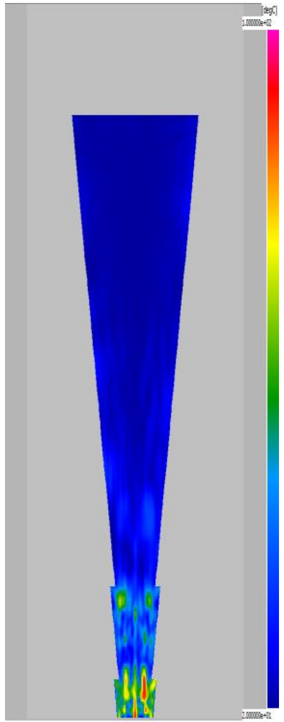




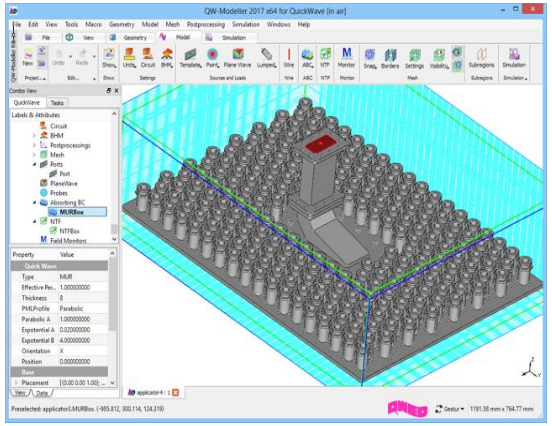
Free-fall waste processing on ships (Eureka FOODWASTE)



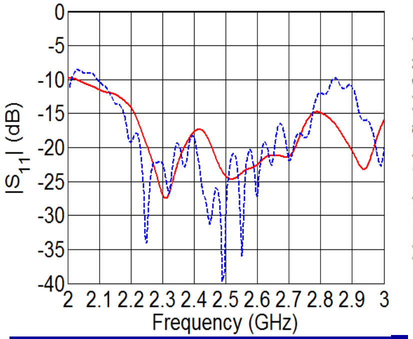
E-field in horizontal & vertical cut

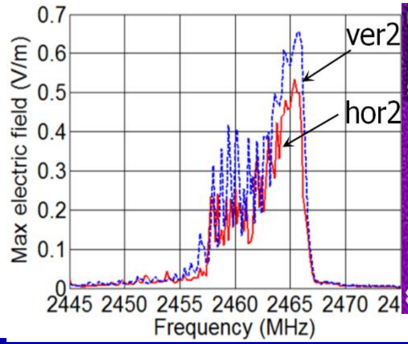


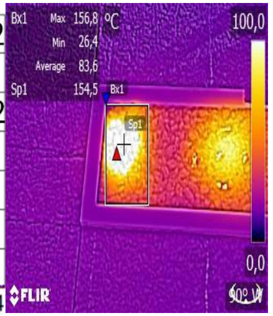
High power applicator for MW treatment of bituminous surfaces (road repair, NGAM project)

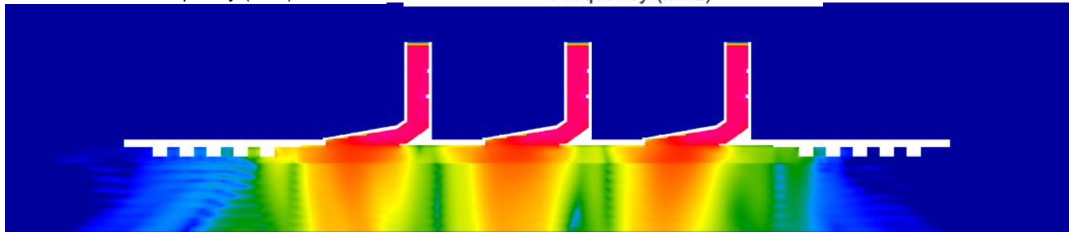


convenient CAD input







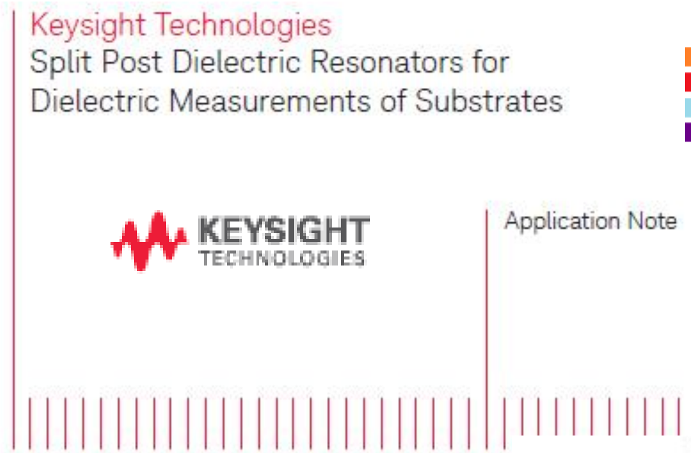


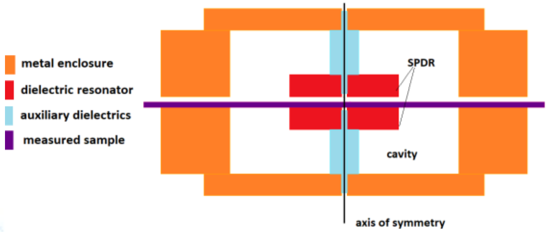
System of three MW power applicators with feeding system and leakage preventing chokes: designed, manufactured, tested

B.Salski et al., *IEEE MTT Trans.*, vol.65, Sep.2017.

Test-fixtures for precise material measurements

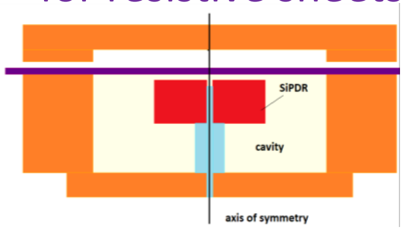
Split-post dielectric resonators for low-loss laminar dielectrics
subject of European Standard IEC 61189-2-721:2015
endorsed by Keysight Technologies Option 003 N1500A



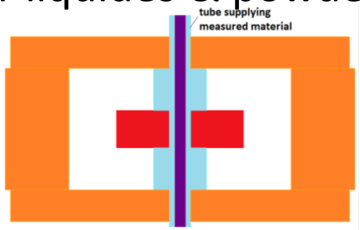


Other commercially available TE01δ resonators

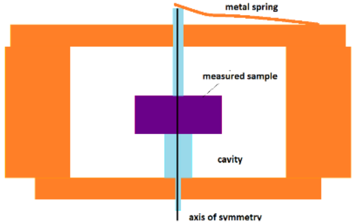
single-post
for resistive sheets



cavity
for liquides & powders

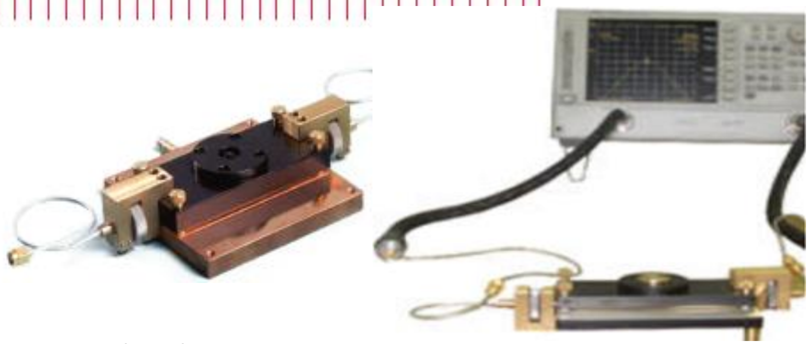


cavity
for bulk samples

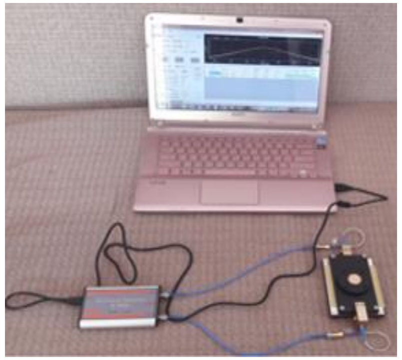


Robust, easy-to-use with:

standard
VNA

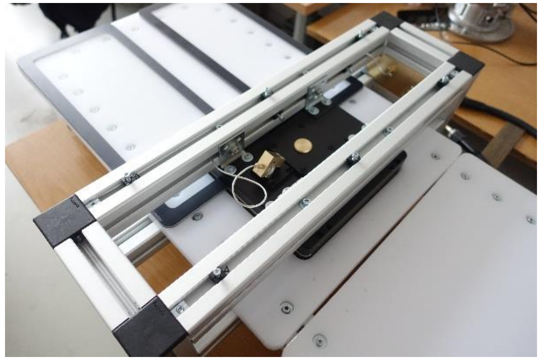


QWED portable
low-cost Q-Meter

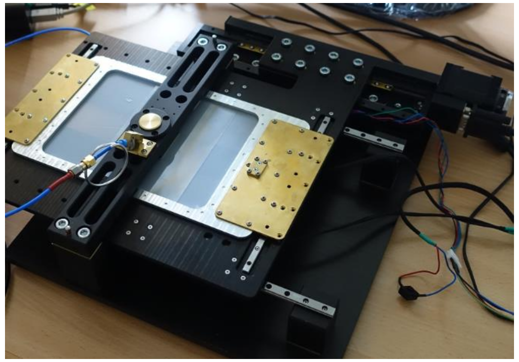


Recent SPDR-based designs for larger surfaces of:

large sheets of glass
manual scan @1.9 GHz



semiconductor wafers
automatic scan @10 GHz

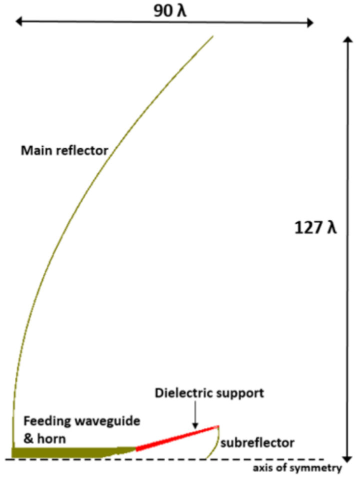


QWED standard SPDRs @ 1.1, 2.45, 5, 10, 15 GHz

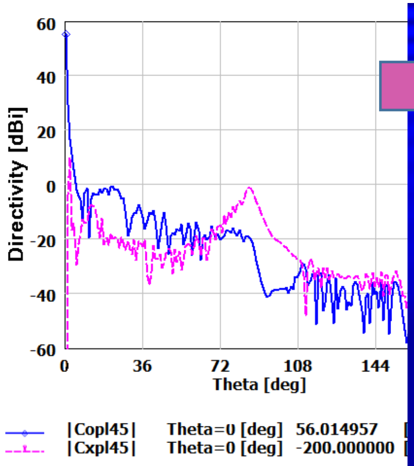
Ref.: www.qwed.eu
J. Krupka et al., *J. Eur. Ceramic Soc.*, vol. 21, pp. 2673-2676, 2001.
J. Krupka & J. Mazierska, *IEEE Trans. Instr. Meas.*, vol. 56, no. 5,2007.
M. Celuch & al., *IEEE MTT-S IMS*, Boston 2019.
www.mmama.eu recent work under H2020-NMBP-07-2017 grant MMAMA No. 761036

Basic near-field workflow - insight into device performance

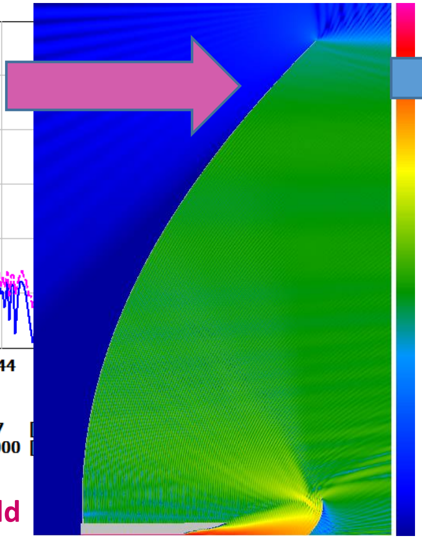
Unique, ultra-fast vector 2D Bessel & FDTD hybrid solver for design & analysis of devices with axial symmetry

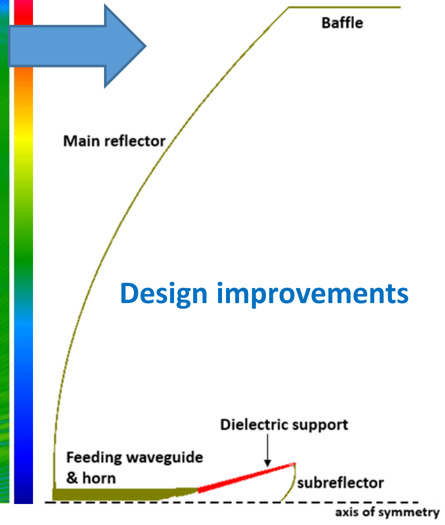


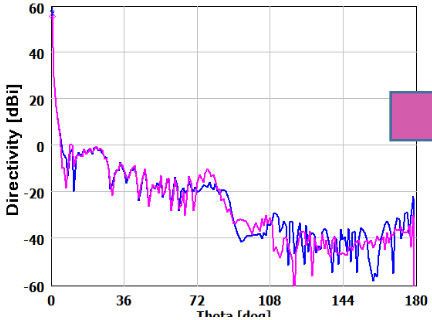
Dual -reflector antenna

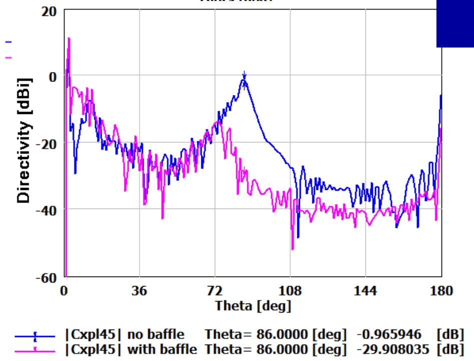


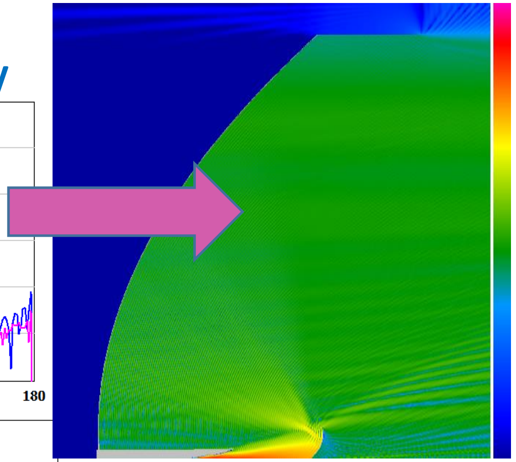
Insight into EM near-field





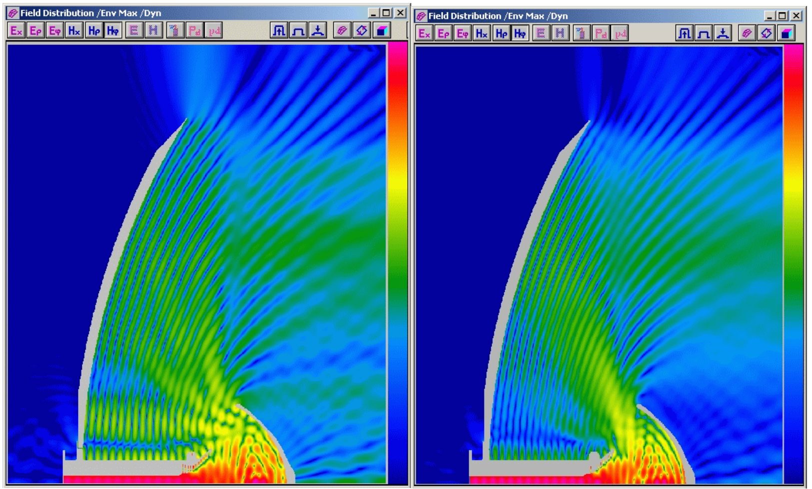






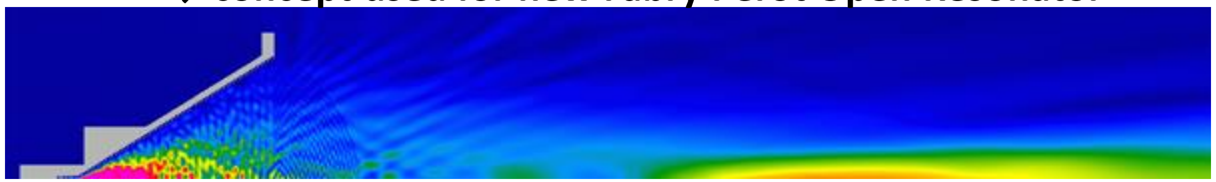
9m – diameter main reflector
Meshing: **λ/40**
Time to solution: **8 min**
Radiation pattern **@24 freq.**,
Δθ=1deg : **5 s**

A different cause of spillover from a bi-reflector antenna:
Hϕ amplitude in logarithmic scale shows FPOR at feed
from max (purple) down to -60 dB (blue) at two freqs. within 3 %



BOR FDTD

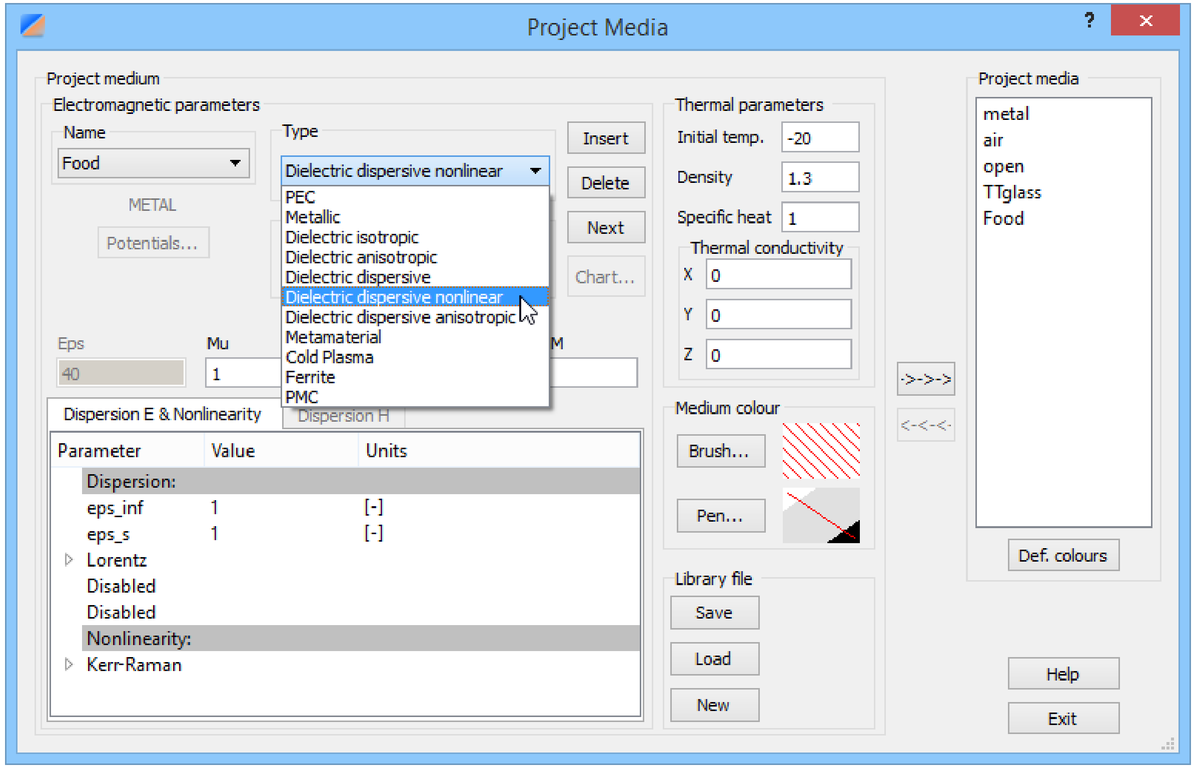
Gaussian beam formation for quasi-free-space material measurements
→ concept used for new Fabry Perot Open Resonator

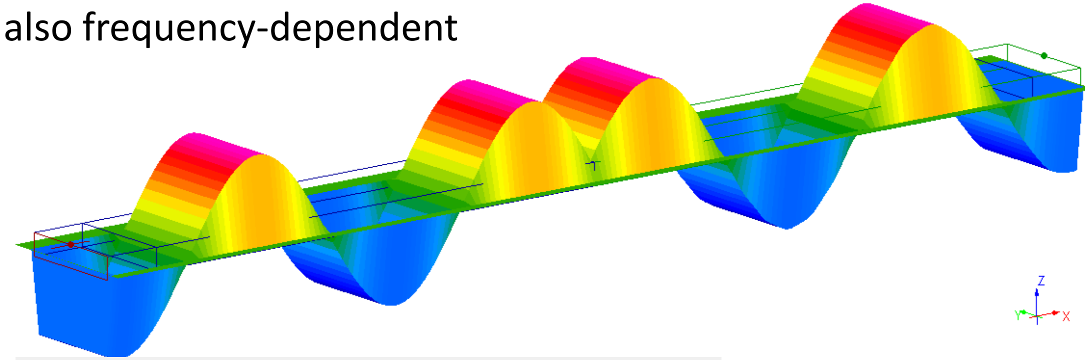


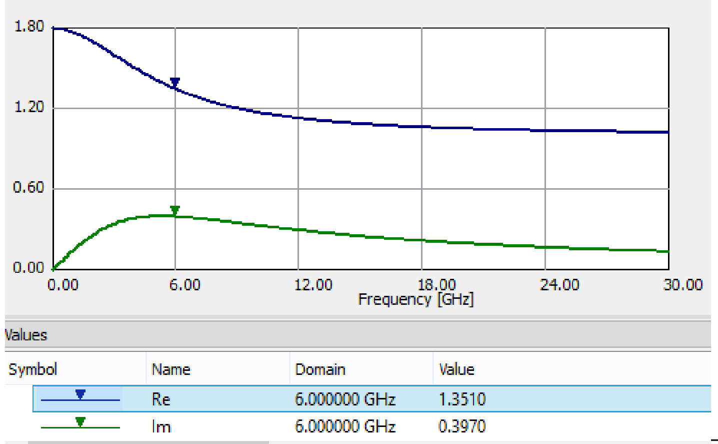
Scenarios modelled full-wave: 250 λ (in each dir.) modelled on average laptop
2500 λ on popular PC
5000 λ on top-shelf PC

Material parameters in EM analysis (1)

Various types of materials modelled by their macroscopic parameters – also frequency-dependent







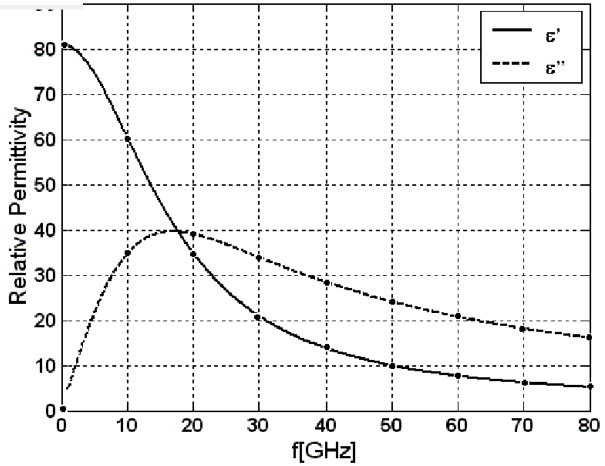
Arbitrary Debye model parameters from QuickWave 3D

Drude: $$\varepsilon_r(\omega) = \varepsilon_\infty + \frac{(2\pi f_p)^2}{(j\omega 2\pi \nu_c - \omega^2)}$$

Debye: $$\varepsilon_r(\omega) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{(1 + j\omega\tau)}$$

Lorentz: $$\varepsilon_r(\omega) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty (2\pi f_p)^2}{((2\pi f_p)^2 + j\omega 2\pi \nu_c - \omega^2)}$$

material parameters from equations



Water parameters

Bilateral coupling of various processes - EM-thermal workflow

FDTD analysis with sinusoidal excitation at *f=f0*

Calculation of 3D pattern of ***dissipated power*** $P_{avg}(x,y,z)$

Enthalpy update in 3D domain

$$H^{n+1}(x,y,z) = H^n(x,y,z) + \frac{P^n_{avg}(x,y,z)\Delta\tau^n}{\Delta V(x,y,z)}$$

Temperature update in 3D domain
$T(x,y,z) = T[H(x,y,z)]$
from *.pmo file

Load movement/rotation
Translation of the object and thermal quantities along user-defined trajectory

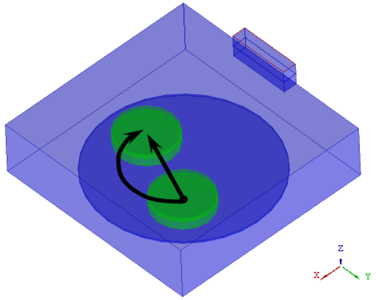
Calculation of heat transfer
Enthalpy and ***temperature*** update in 3D domain

Material and ***thermal parameters*** update in 3D domain $\varepsilon(x,y,z) = \varepsilon[T(x,y,z)]$
$\sigma(x,y,z) = \sigma[T(x,y,z)]$
from *.pmo file

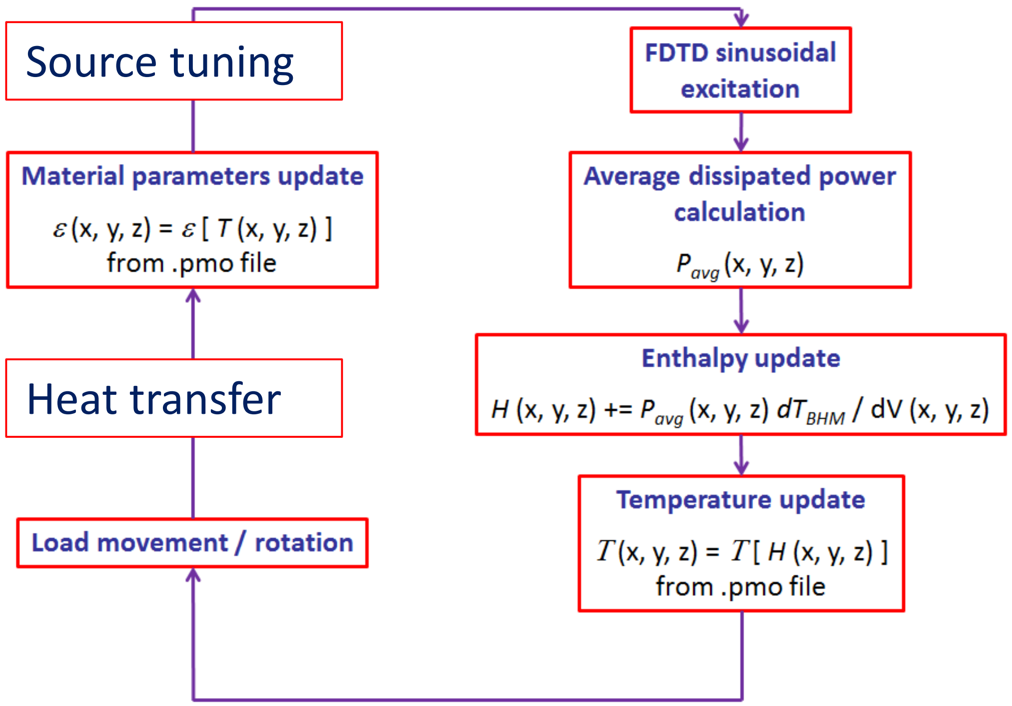
Source tuning to *f=f1*
Changing operating frequency: automatically to the deepest resonance or manually upon user's criterion

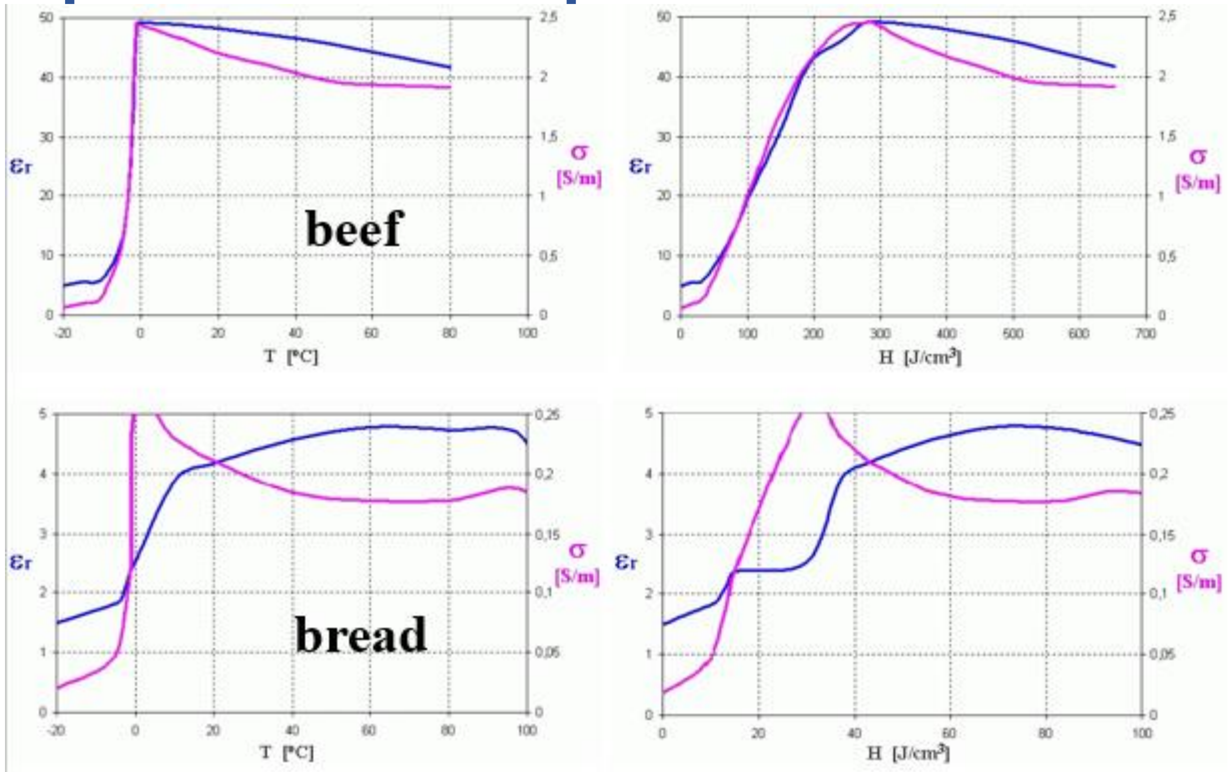
material parameters from user's text files (private data base)

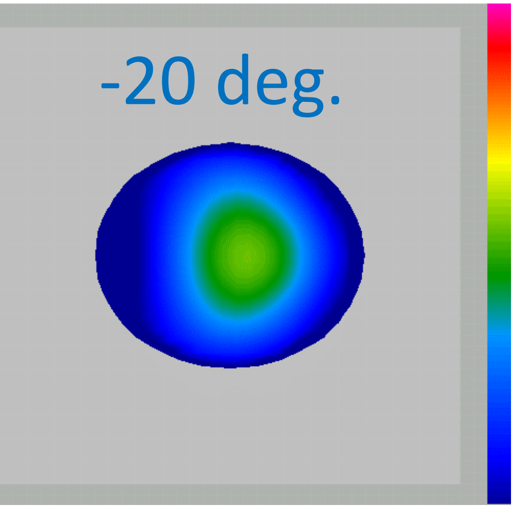
```
#Raw beef draft media file for QW-BHM module (00-09-06 POR)
#Measurements & refinements by Per O Risman, Microtrans AB, Sweden
#Modified by QWED, Poland
# DATA FROM -20 C to +80 C, dH/dV in J/cm3 reversedEnth/Temp column
!Temperature    Enthalpy        EPa             SIGa    SpecHeat Density  Ka
# Data deg C    J/cm3                           S/m
-20             0               4.9             0.064   2.21    1.06    0.0069
-15             14.0            5.5             0.093   2.21    1.06    0.0069
-10             34.4            6.1             0.153   2.21    1.06    0.0069
-5              71.4            12.3            0.573   2.21    1.06    0.0069
-3              110.4           22.0            1.118   2.21    1.06    0.0069
-2.2            144.4           30              1.636   2.21    1.06    0.0069
-1.6            192.4           42              2.113   2.21    1.06    0.0069
-1.3            240.4           46              2.385   2.21    1.06    0.0069
-1.1            274.4           48.9            2.426   2.21    1.06    0.0069
-1.0            288.4           49.2            2.440   2.21    1.06    0.0069
10              327.9           48.9            2.317   2.21    1.06    0.0069
20              382.9           48.2            2.194   2.21    1.06    0.0069
35              450.4           46.9            2.072   2.21    1.06    0.0069
50              517.9           45.5            1.949   2.21    1.06    0.0069
65              585.4           43.6            1.922   2.21    1.06    0.0069
80              652.9           41.7            1.908   2.21    1.06    0.0069
```

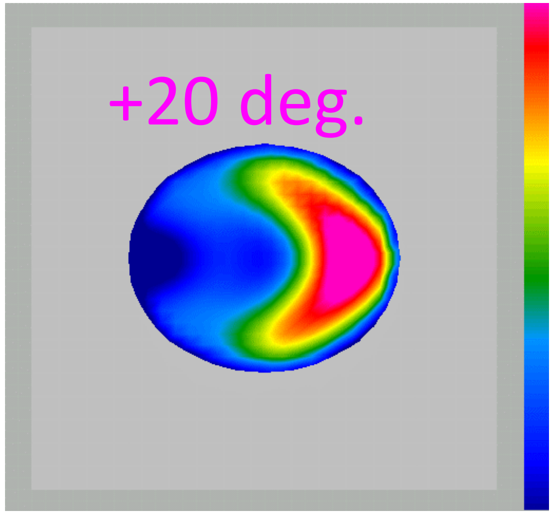


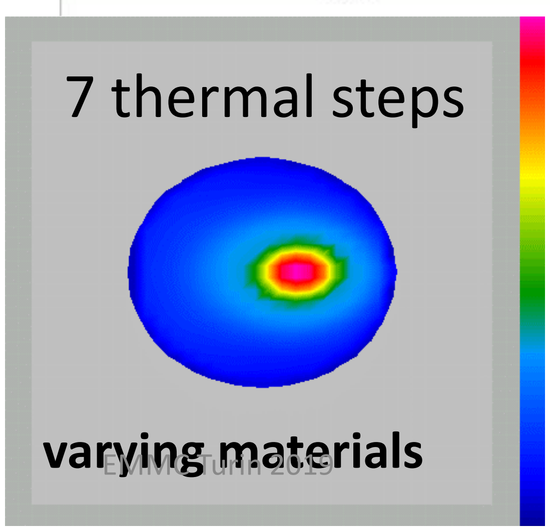
Multiphysics modelling: temperature-dependent materials











QW-BHM module of QuickWave:
- **automatic system**
- **each cell heated individually**
- **no need to define 1000s of "media"**
- **bilateral coupling EM - thermal**

QW-BHM coupled workflow and its impact on QWED customers

2000 - making users' life easier:

"I no longer need to define 100 *sausage media* to model one sausage!"

"It was and is particularly helpful in the studies of the progress of defrosting in microwave ovens,
assisting in the quantification (and experimental verification) of the influences of the underheating
(longitudinal section magnetic, LSM) modes between the cavity bottom and the shelf with food item.
This has helped a lot in later developments of new oven models at Whirlpool.
– It is also helpful in studies of the edge overheating effect, but then mainly in work with optimisation of geometries of containers and quantifications of the influence of salt content of e.g. sauces, then for development of microwaveable ready meals.
– Generally speaking, **use of the BHM module did a lot of experimental work obsolete**,
and by that **saved both time and money in industry**. "

2019 – providing "freshly baked" functionalities to our users:

"I attach the fresh paper! As you can see, we have used both your subtraction option and the Austin man head (..)!"

Basic Heating Module → Block of Hybrid Modules

I believe in coupling (hybridisation) but it must be bilateral and...

...implemented with the adequate understanding of the physics!!!

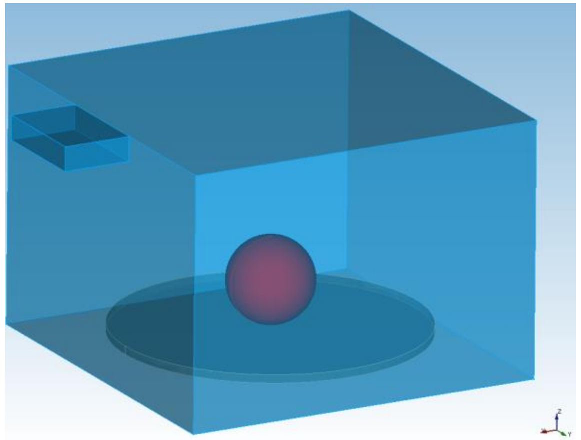
QWED offers flexible interfaces
& seeks collaborations to "couple"

Accurate modelling of coupled electromagnetic-thermal problems

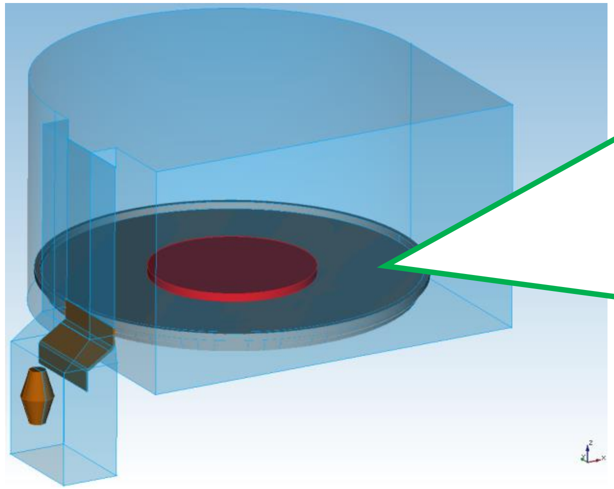
Verification & validation

Simple microwave heating benchmarks & microwave heating phenomena studies*

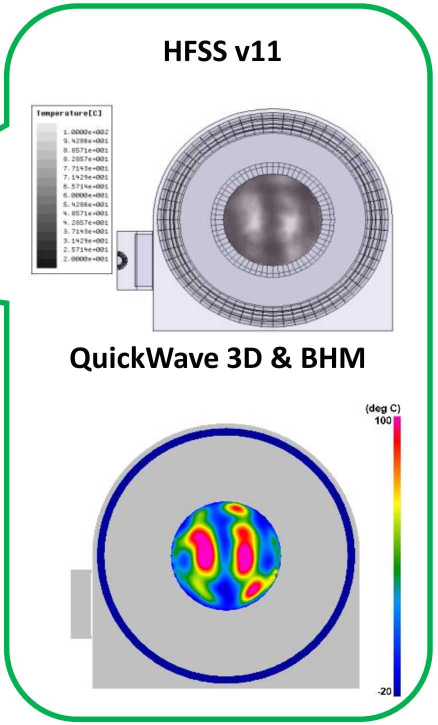
Design & analysis of real-life microwave oven cavities, incl. complicated cavity shapes and advanced feeding system*



- heat transfer & load dynamics
- Load rotation & arbitrary movement during heating
- Source parameters tuning – regime for solid state sources
- Temperature dependence of material parameters

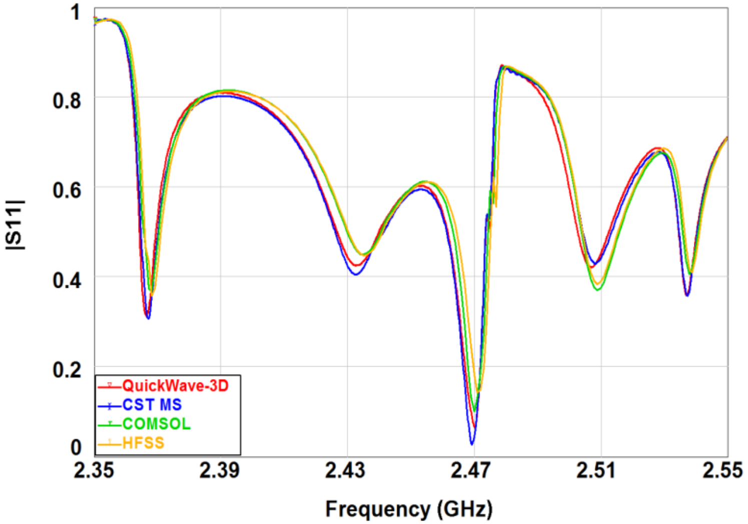


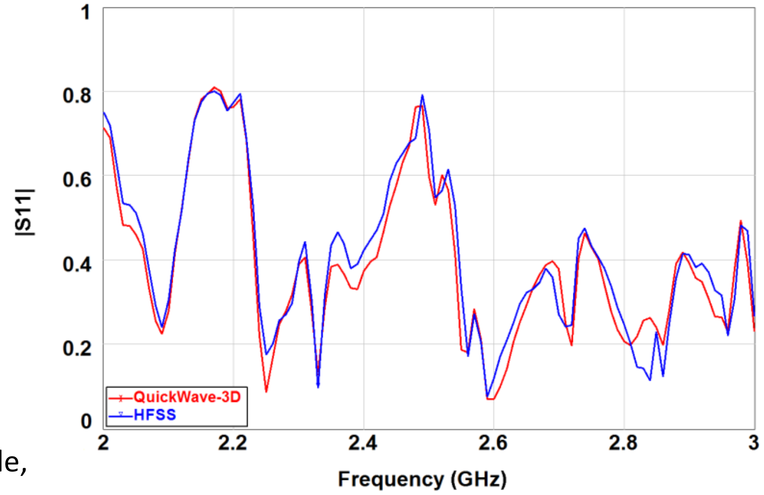
Courtesy of Whirlpool Inc. – Whirlpool MAX oven



Freezing to file the state of the simulation

De-freezing on arbitrary computer & at convenient time



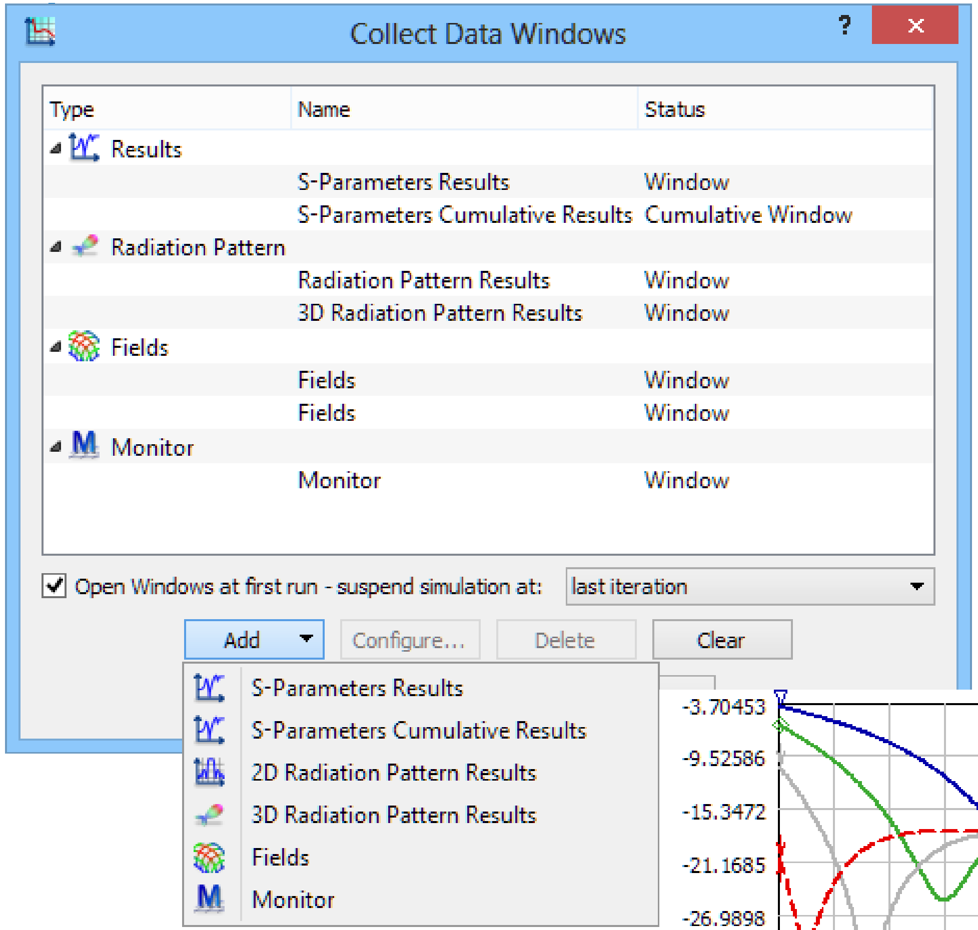


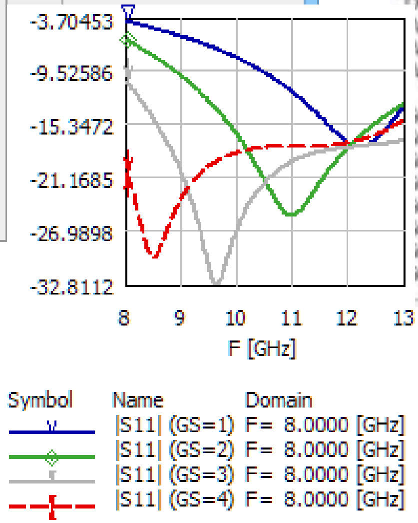
With QuickWave EM computation as fast as **1 min 18s** on a **low-cost video card** – supporting **all** graphic cards **with OpenCL**

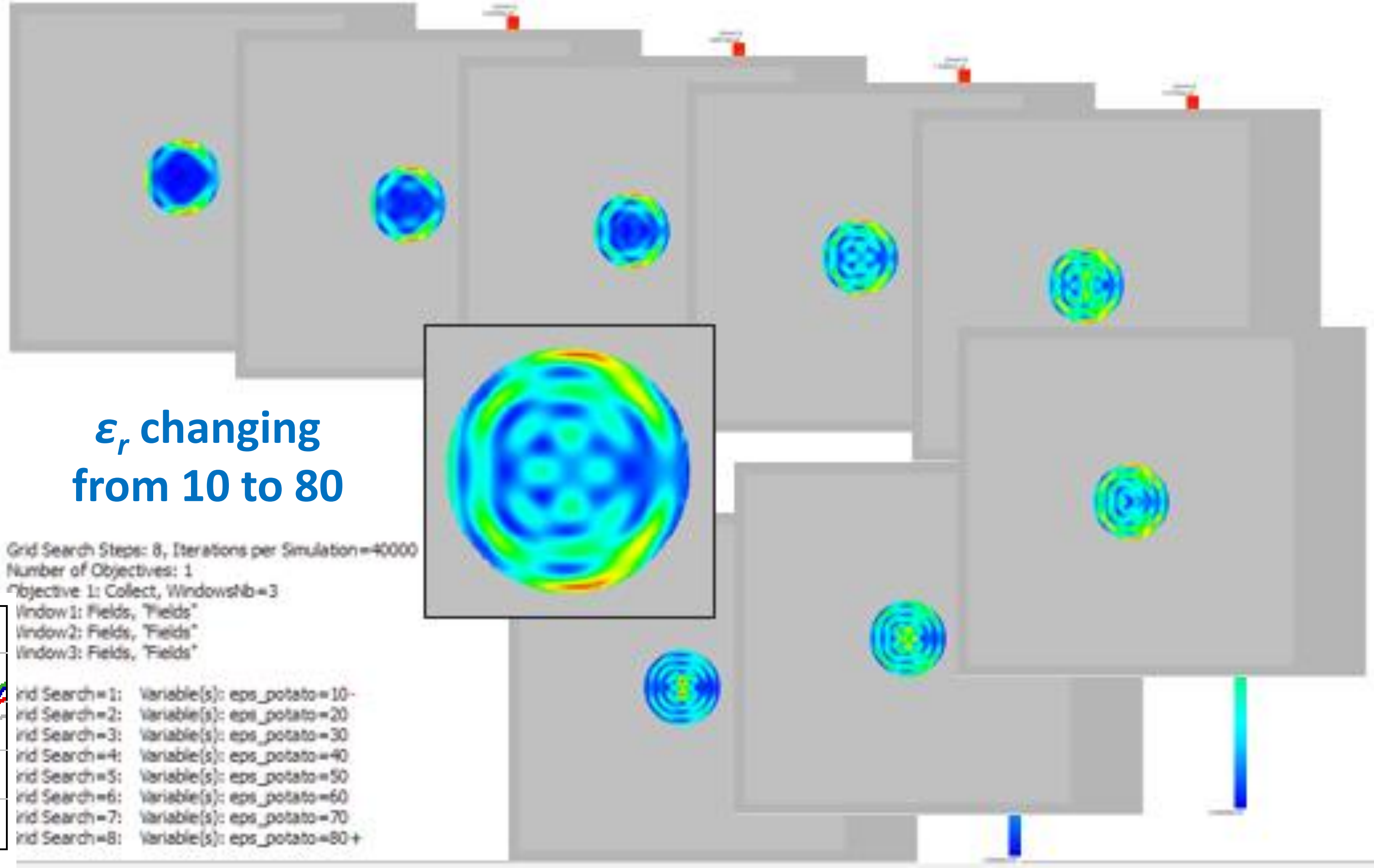
* Considered by M.Celuch, P.Kopyt & M. Olszewska-Placha in eds. M. Lorence, P. S. Pesheck, U. Erle, *Development of packaging and products for use in microwave ovens*, 2nd Ed. Elsevier in print.

Multiphysics modelling: *Collect Data* in *Grid Search* workflow

Collect Data **of S11 and dissipated power density in potato heated in MW oven, as text files and GUI**







ε_r changing from 10 to 80

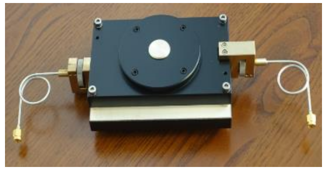
Note: automatic multiple switching from pulse to sine excitation implemented in QuickWave for matching source to load.

Continuum modelling of thin conductive sheets

Thin conductive sheet

Measurements of Surface resistance

Single-post dielectric resonator

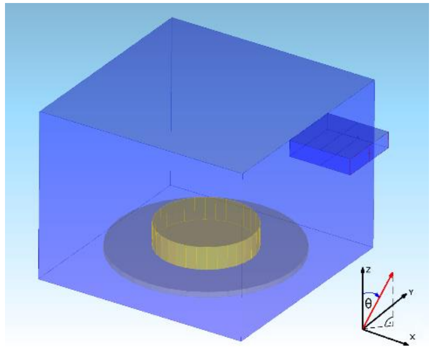


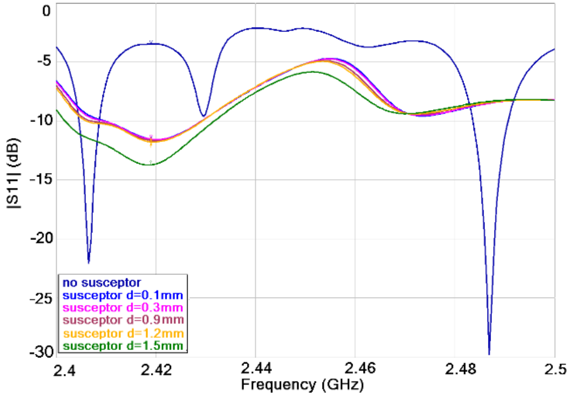
Split-post dielectric resonator

$$R_s = \frac{1}{\sigma h}$$

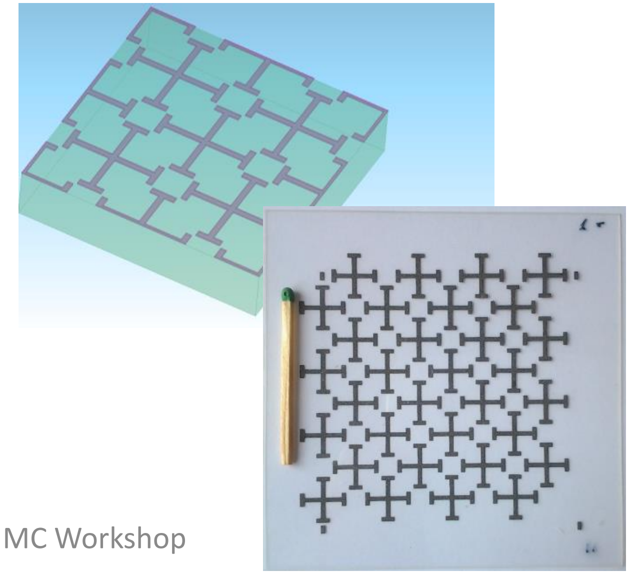
Simulation model

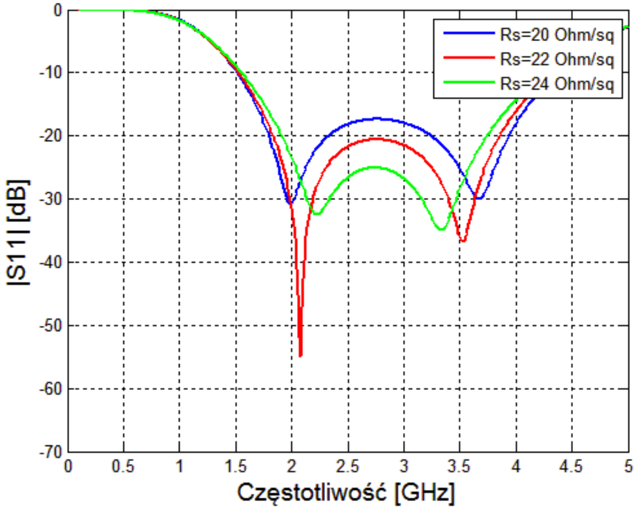
Thin conductive sheets in application to MW susceptors for enhancing food processing in domestic MW ovens





Thin sheets of carbon-based polymer composites described with surface resistance in [Ω/□] in application to wideband MW absorbers

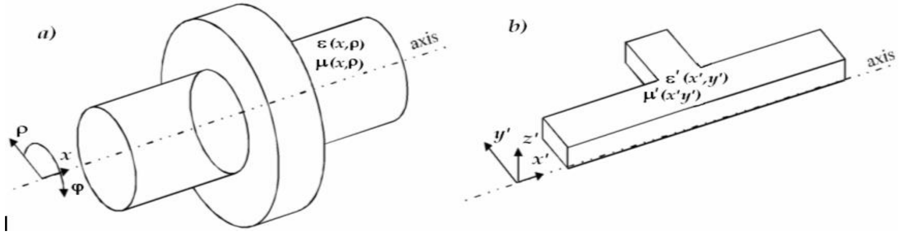




Efficiency of the modelling is enhanced by using **pre-measured effective** material parameters

Clever material modelling can reduce problem dimensionality!

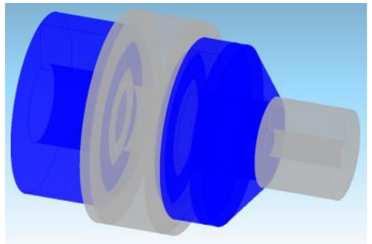
Reduce 3D axisymmetrical problem (a) to planar 2D (b):

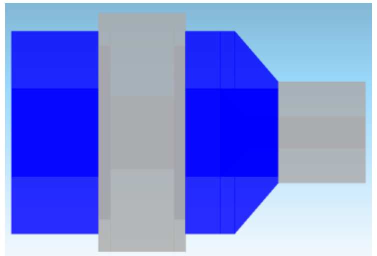


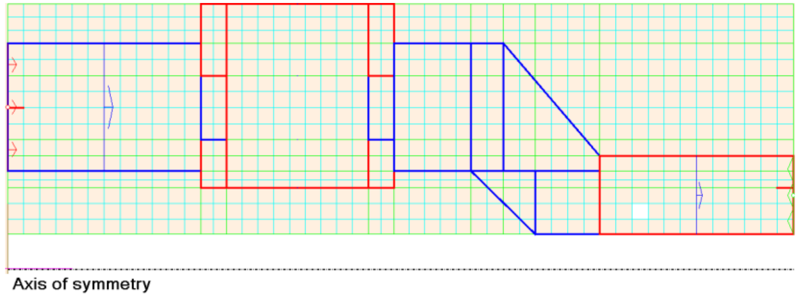
Apply Maxwell equations in cylindrical coordinates:

- **numerical** FDTD discretisation in 2D plane ($x\rho \rightarrow x'y'$)
  → economies in computer effort by 2-3 orders in magnitude

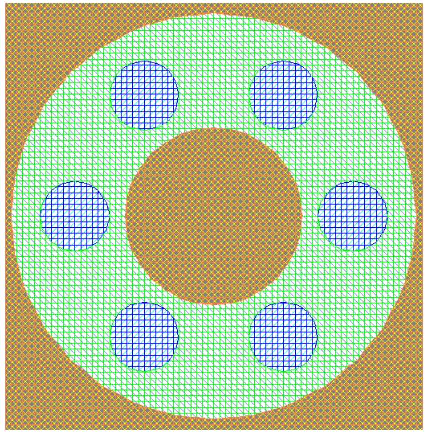
- angular cos($n\varphi$) / sin($n\varphi$) field dependence enforced **analytically**
  → expected higher accuracy for high-n modes







Perforated coaxial cables



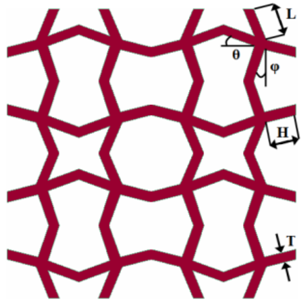
3D problems

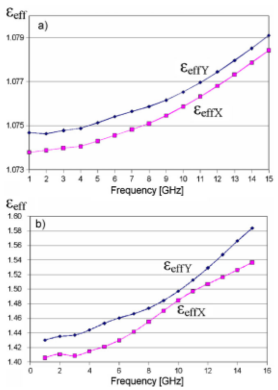
-> reduce to 2D (long-section) with effective dielectric whose parameters are obtained by 2D quasistatic modelling of coax cross-section

-> efficiency enhanced by over an order in magnitude

"Since we have developed trust in QuickWave, we do not prototype any longer".

Similar modelling also used to design structural chiral new materials

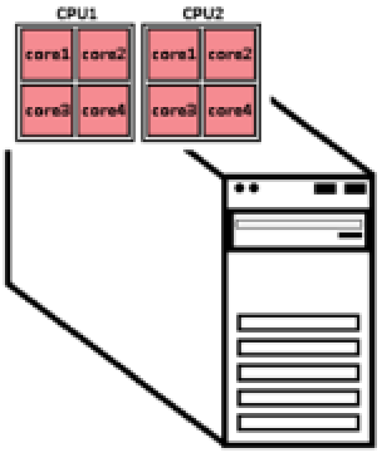




F.Scarpa et al. PSSB, vol.246,no. 9,2009.

Following hardware breakthroughs

Using **Open MP** standard to accelerate FDTD calculations and to separate fast FDTD calculations and graphics (simulation results' displays



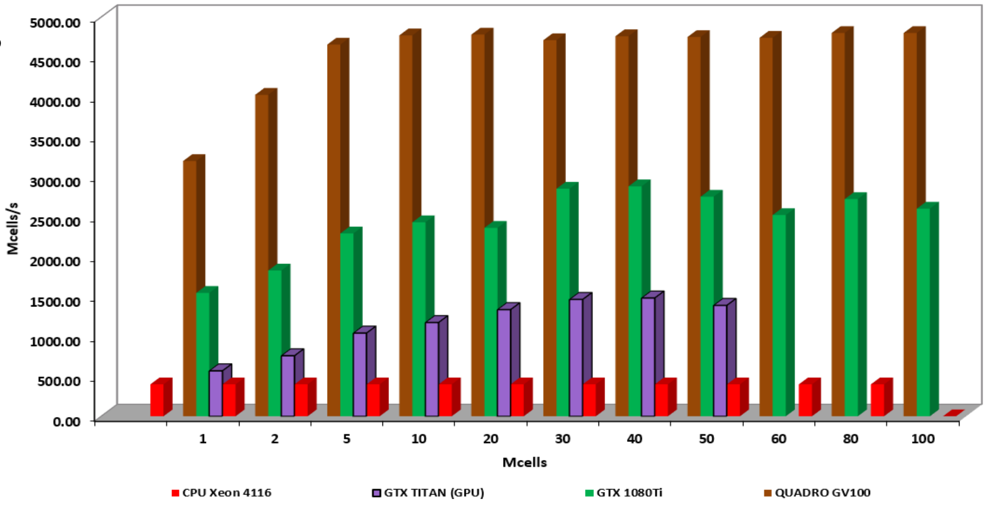
All QuickWave functionalities included

GPU and MultiGPU computations

Challenge: using the right programming platform:

CUDA vs **OpenCL**

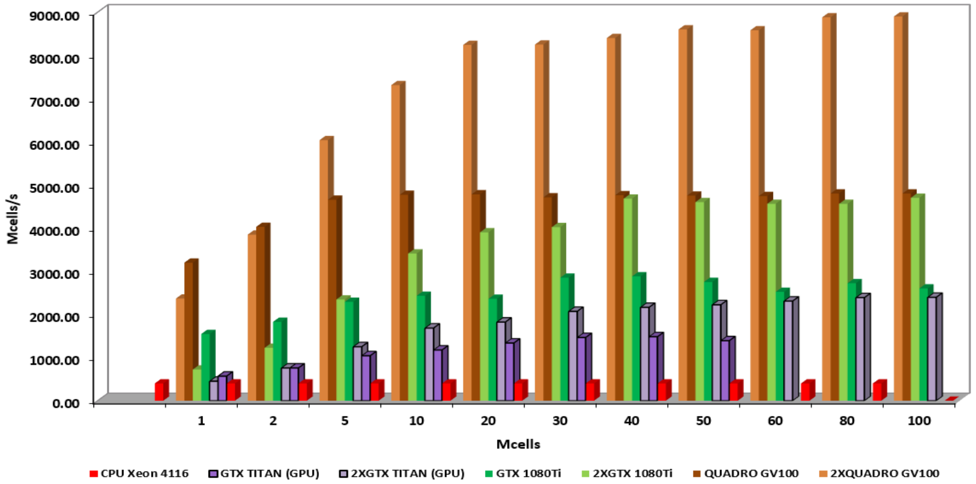
Expensive professional computation nVidia cards



GPU acceleration of QuickWave 3D

Time to solution decreased even **10 times** comparing to powerful CPUs

Also low cost video cards (with good performance parameters) of different manufacturers



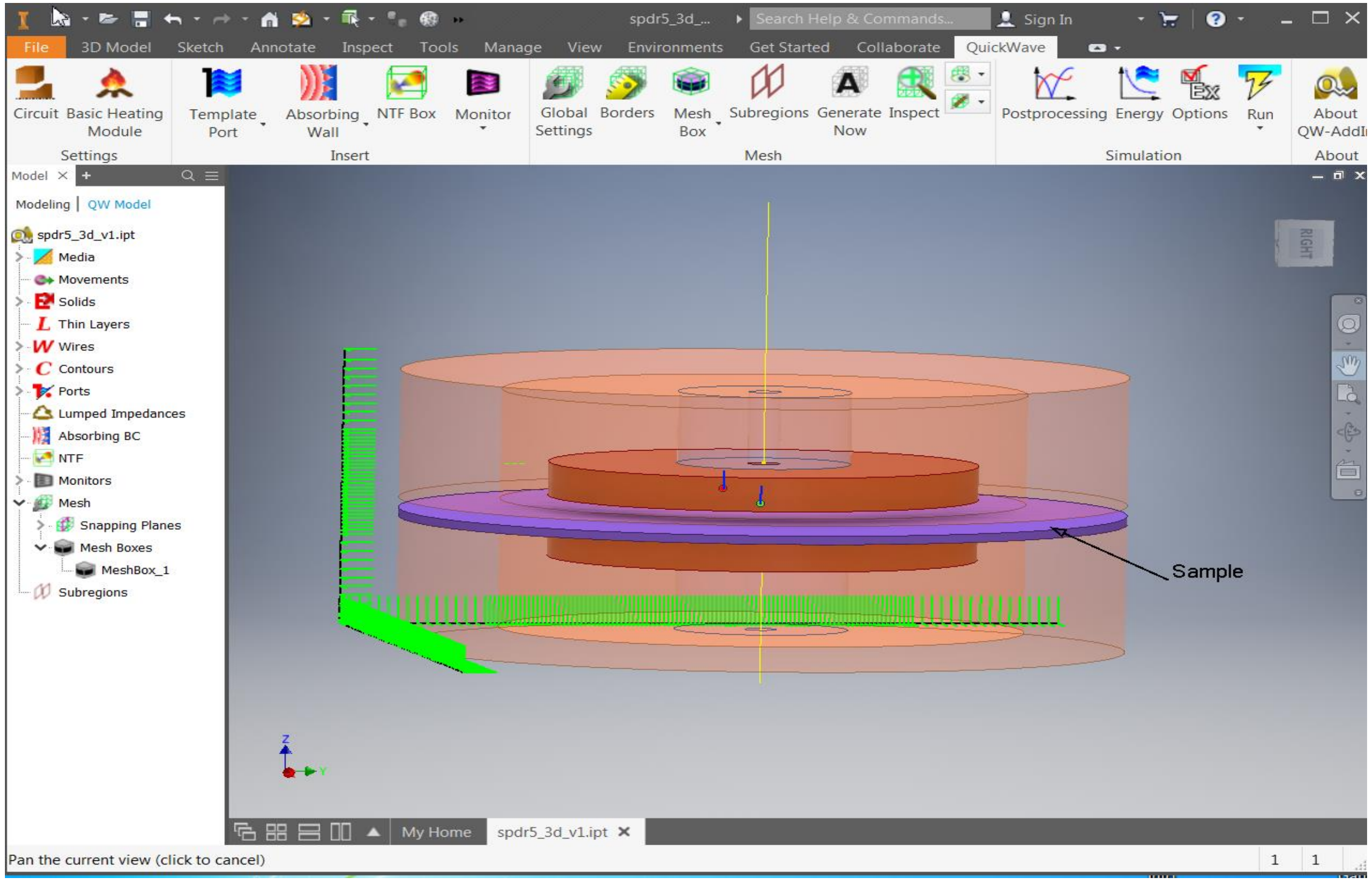
MultiGPU acceleration of QuickWave 3D

Time to solution decreased even **18 times** comparing to powerful CPUs (..but only 1-2% of users...)

Modelling workflow for validation of SPDR method assumptions

How much is the E-field pattern influenced by SUT?

→ application of "*near field imaging*" in QuickWave



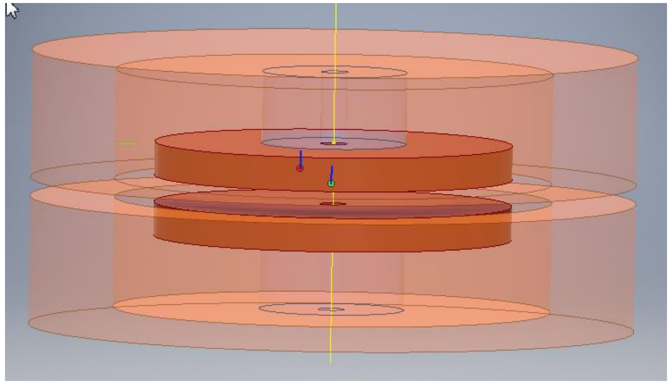
10 GHz SPDR model in QW-AddIn for Autodesk® Inventor® Software

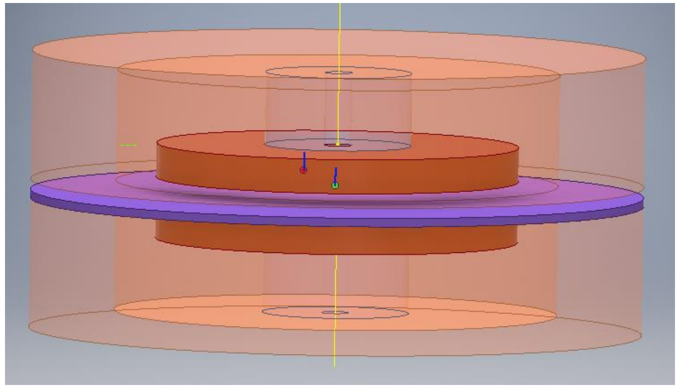
Modelling workflow for validation of SPDR method assumptions

How much is the E-field pattern influenced by SUT?

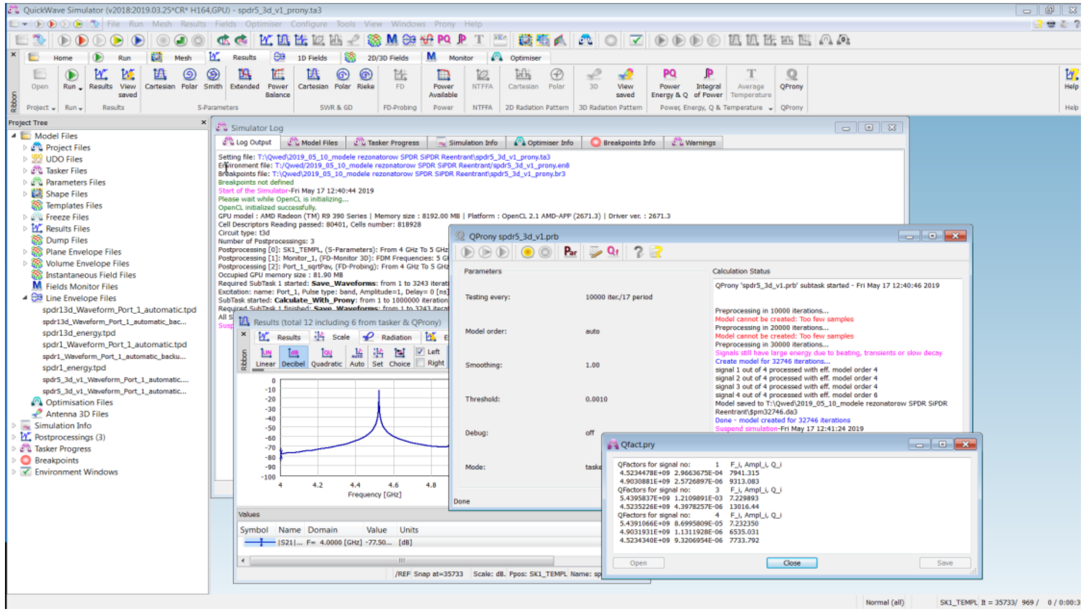
→ application of "*near field imaging*" in QuickWave

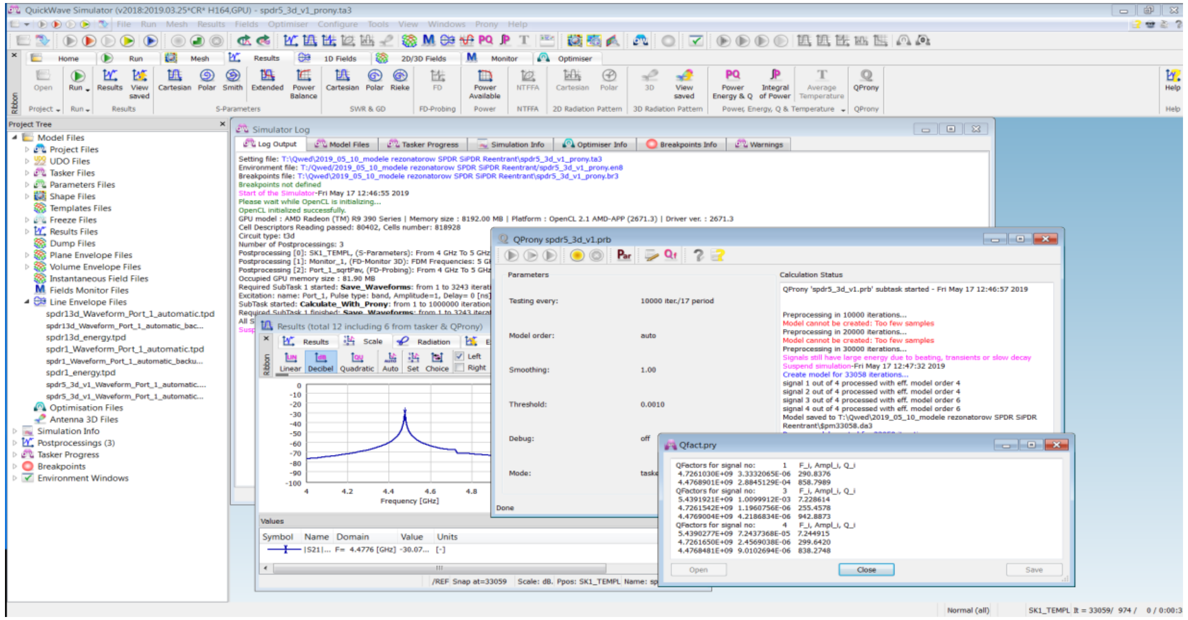
empty





with SUT

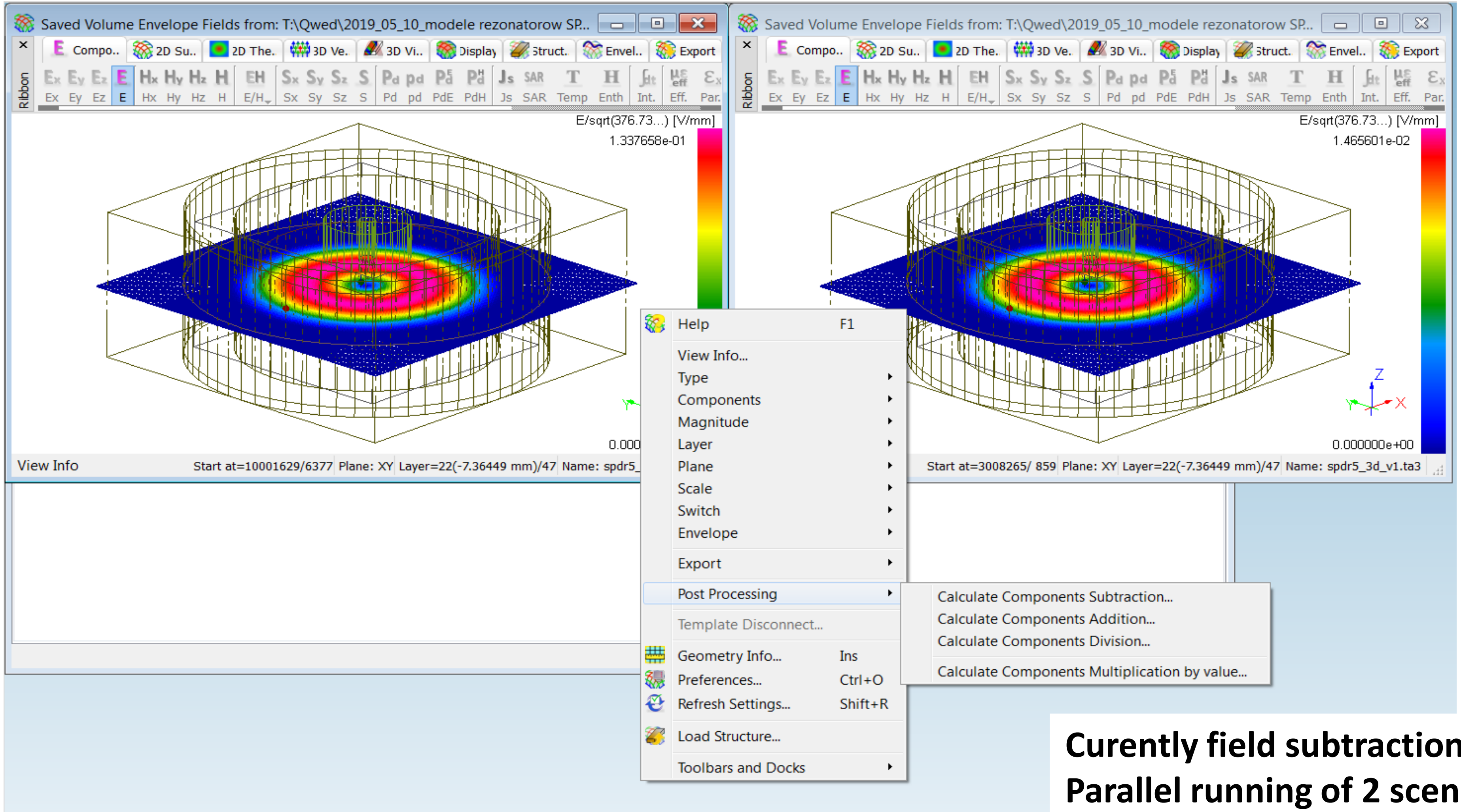




Modelling validation of SPDR method assumptions

How much is the E-field pattern influenced by SUT?

→ application of "*near field imaging*" in QuickWave



field subtraction workflow

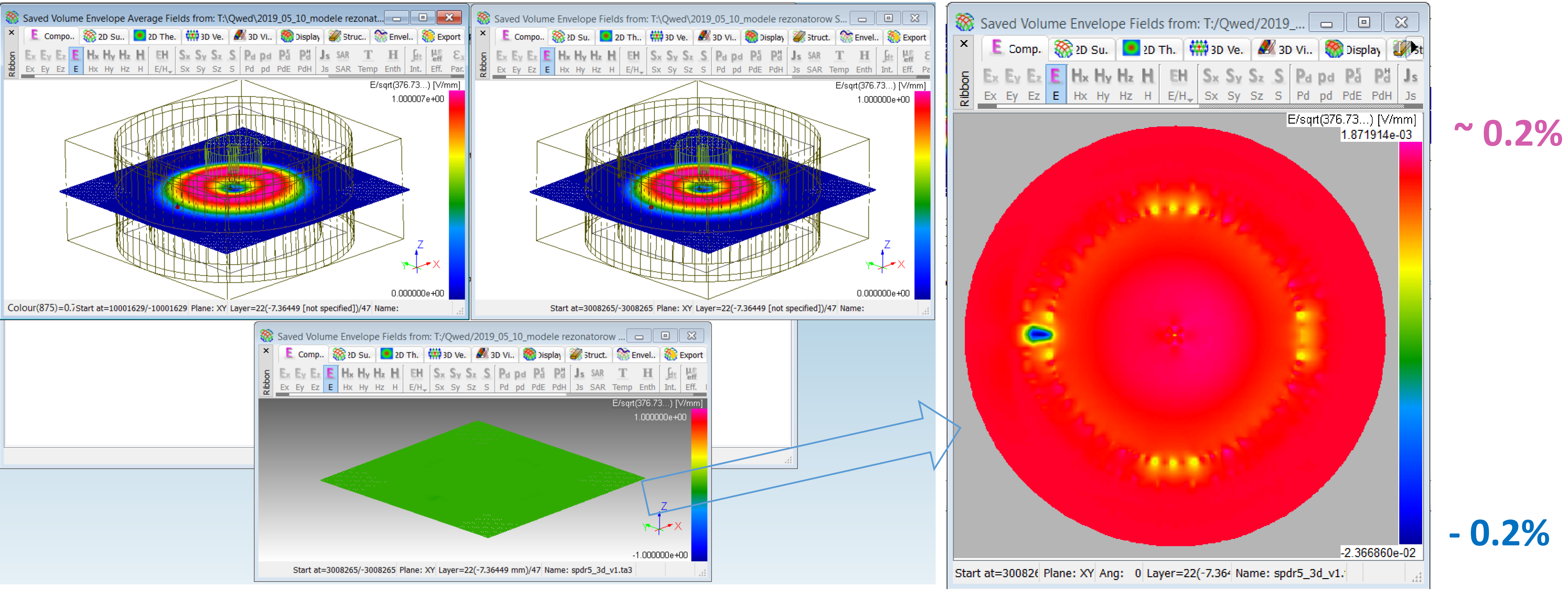
two linked models

Curently field subtraction performed on saved fields.
Parallel running of 2 scenarios under development.

Modelling validation of SPDR method assumptions

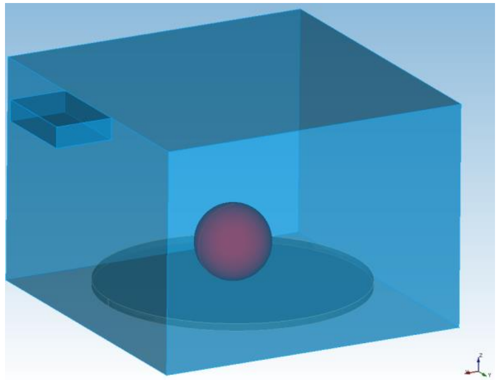
How much is the E-field pattern influenced by SUT?

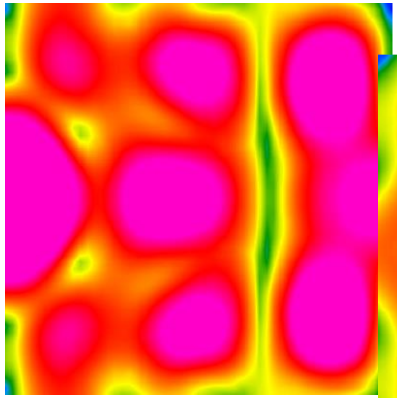
→ application of "*near field imaging*" in QuickWave



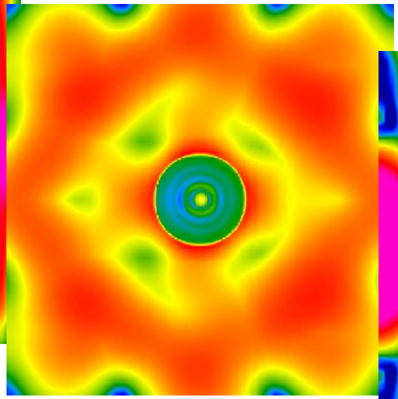
Advanced (linked) near-field imaging workflow

Separation of incident and diffracted fields (*option implemented per request of P.O.Risman, Malardalen Univesity*)

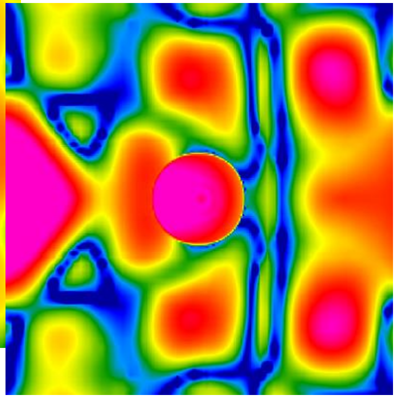




E-field in an empty cavity

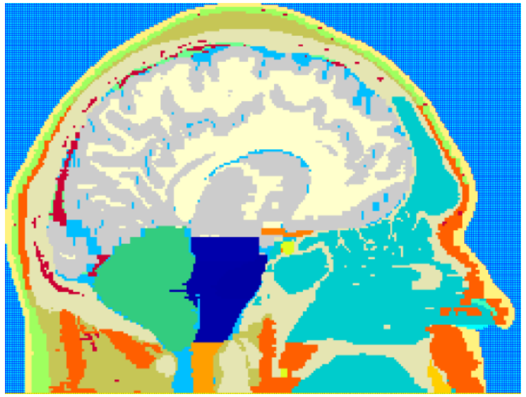


E-field in a loaded cavity

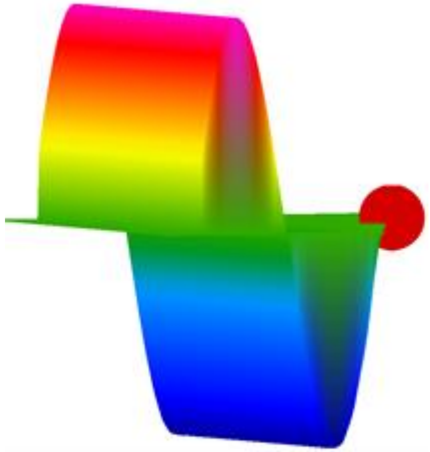


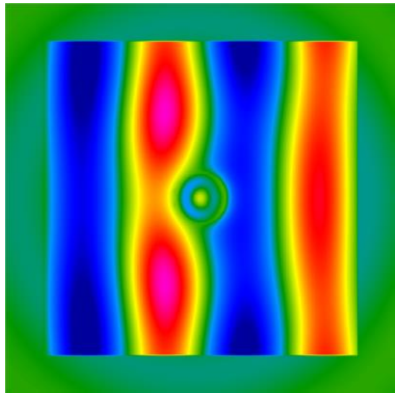
Scattered near-field in cavity

Detection of inhomogenities in tissues

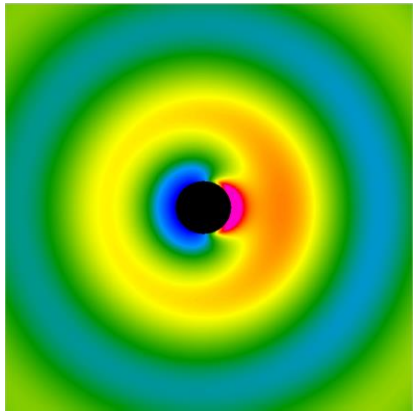


AustinMan model* converted to **QuickWave EM** software for Mälardalen University, Sweden

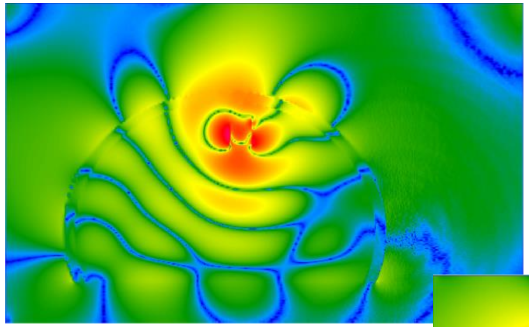


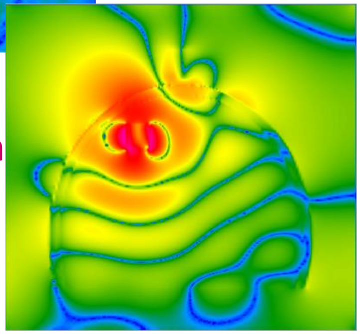


Total field
Focusing by the load
„exploding egg effect"



Diffracted field reveals cause of focusing: circumferential resonance



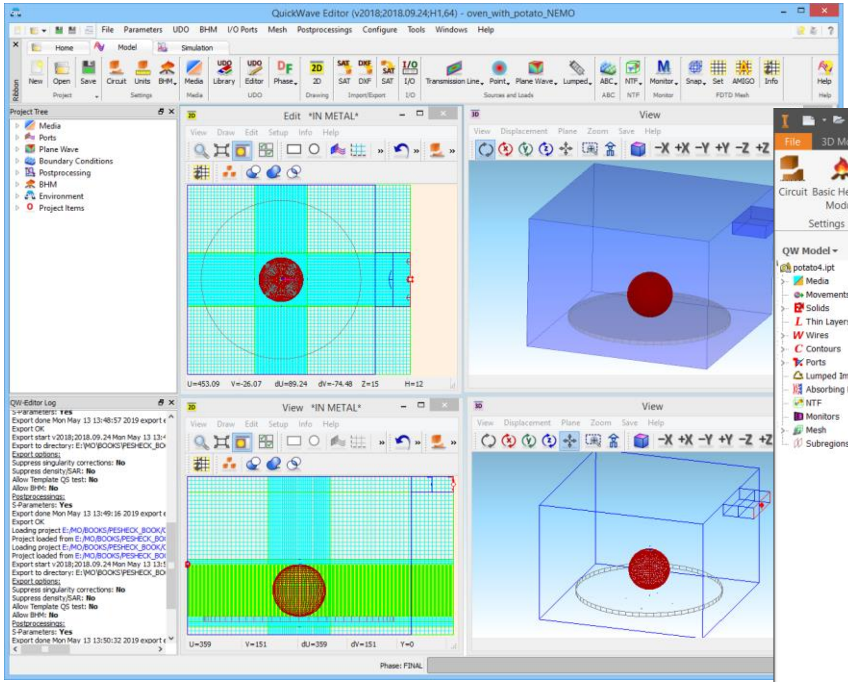


- ✓ **Tumours & haemorrhages detection**
- ✓ **Optimisation of multiantenna tomographic systems**

* https://sites.utexas.edu/austinmanaustinwomanmodels/

Dedicated user interfaces for parametrised project creation

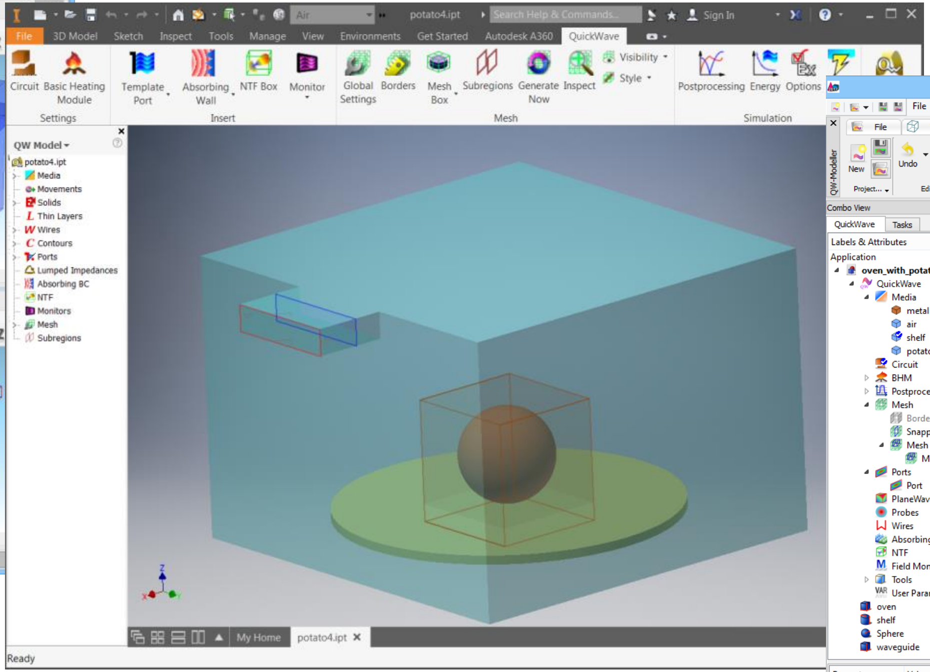
QW-Editor



In-house, script based

Import/export to *.sat & *.dxf

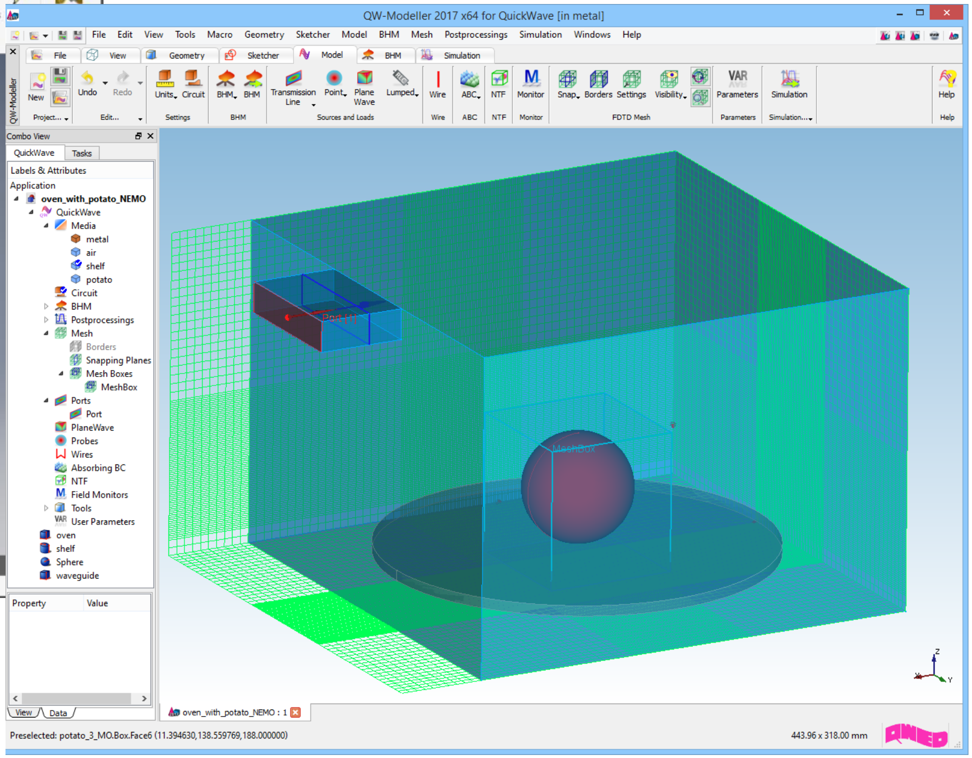
QW-AddIn for Autodesk Inventor Software



Based on advanced professional CAD tool

Import/export to e.g. *.sat & *.step

QW-Modeller
NEW BUSINESS MODEL



CAD tool - FreeCAD based

Free of charge, No licences, No time restrictions, No project limitations

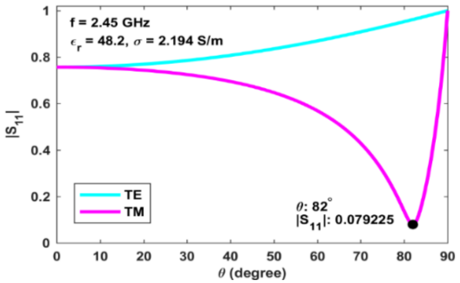
Import/export to e.g. *.step, *.iges & *.dxf

Curiosity: export of CAD files from "old" QW-Editor for further manufacturing is reported by our user.

Conclusions: on software development & business

- EM modelling is a powerful tool for MW design, also for development of new materials & material measurement methods.

- EM modelling workflows help bridging the gaps between seemingly different technology domains:
  - *near field imaging* explains exploding eggs *but also* helps in material measurements,
  - *Brewster angle* is exploited in telecommunications *but also* in domestic MW ovens.



- Modelling lies at the basis of material measurements,
- ...but modelling itself is only as good as the previously measured material parameters
- ...and modelling use used to design materials.

- Two approaches to commercial software development:

- *black box* that quickly provides *solutions = numbers*,
- *virtual laboratory* that provides *physical insight*, but *users' preferences vary*...

- It is possible to set up a business based on a research idea (no initial funding or other forms of support).
- The price to pay for setting up a business is not just financial; it involves change of lifestyle and vast responsibility.
- But a "gem" does not shine forever... QWED business continues with licences/consulting/hardware/R&D projects.

- QW-Modeller & short-term solver licences also form a new business model.
- I believe in coupling but only if well understood in terms of the underlying physics & different scales.
- QWED seeks collaborations & individual enthusiasts.

THANK YOU!