WMG-4

Advances in Computational Modeling and Materials Characterization for the Microwave Power Industry

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[1]**QWED Sp. z o. o.**

Special thanks to Lukasz Nowicki,
QWED's new team member and PhD student at the Warsaw Univ. Tech.,
for his assistance in assembling this presentation.

IMS Booth #2537

Outline

- Motivation & Background:
  - Digital Twin & Its Applications
  - **The Bases & Timeline of QWED Research**
- Computational Physics-Based Modeling of Microwave Heating
- Experimental Acquisition of Material Parameters
- Conclusions

Digital Twin

Computer Aided Design of microwave power systems requires having a “twin” of the physical reality:

Physics Equations

(PE)

Maxwell, heat flow, fluid flow, load movement, …

Material relations

(MR)

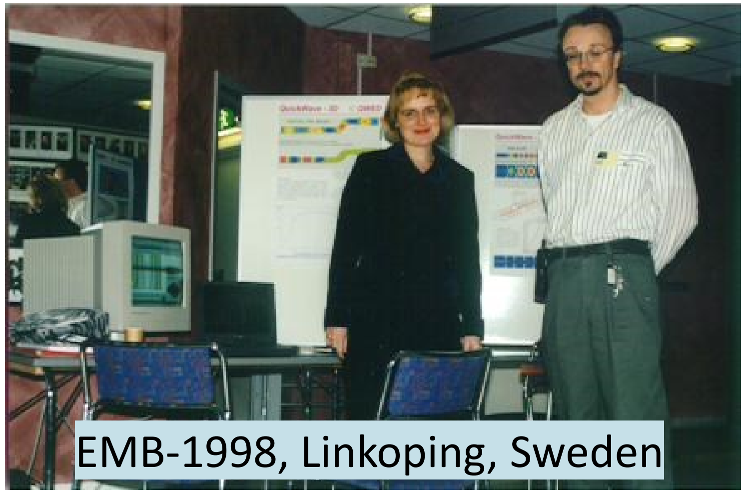
literature data or own measurements

Our team has been active in both areas for over 26 years!

QuickWave TM software

GHz-resonator-based instruments

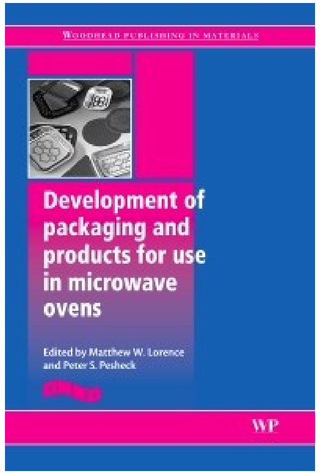
Modeling of MW Heating: Our Early Days

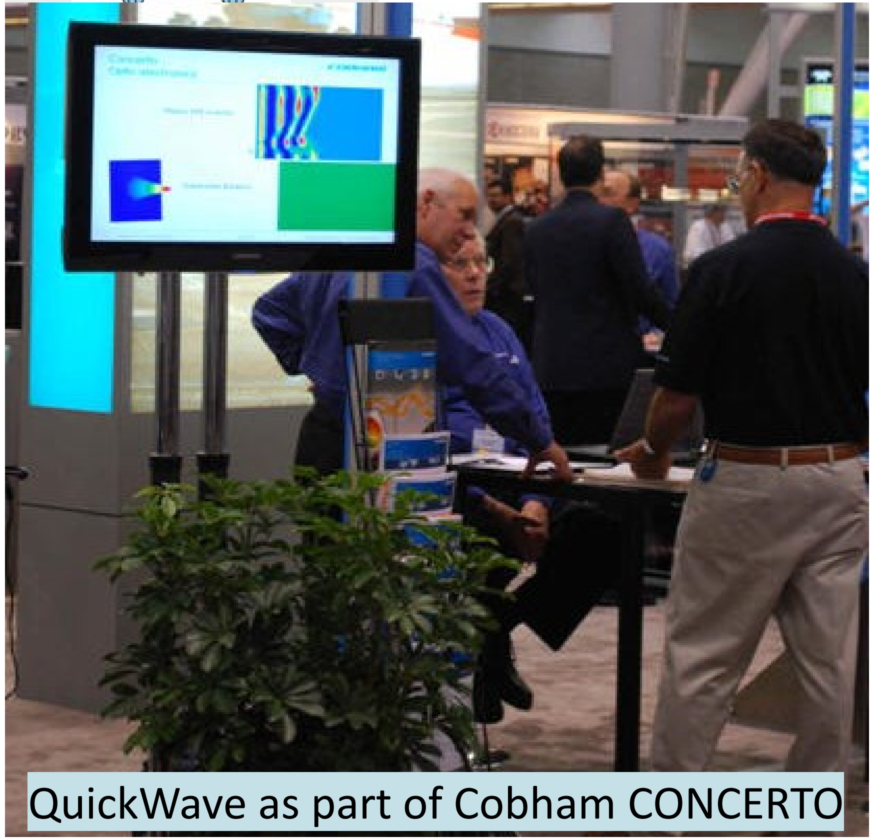

EMB-1998, Linkoping, Sweden


IEEE IMS 2014, Tampa, FL

IEEE IMS 1999, Anaheim, CA

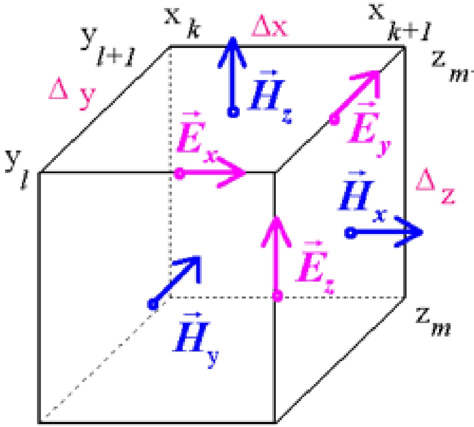
2009 IEEE MTT-S - Boston, MA




QuickWave as part of Cobham CONCERTO

Modeling of MW Heating: Approach

FDTD (Finite-Difference Time-Domain Method): explicit, **fast**, emulates natural physical processes



$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\nabla \times \vec{H} = \frac{\partial \vec{D}}{\partial t}$$

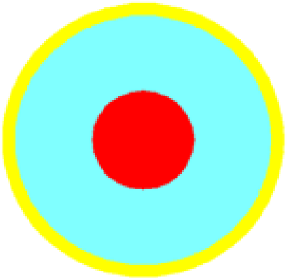
$$ {}_{k,l,m+0.5}E_z^n = E_z(x_k, y_l, z_m + 0.5\Delta z, t_0 + n\Delta t) $$

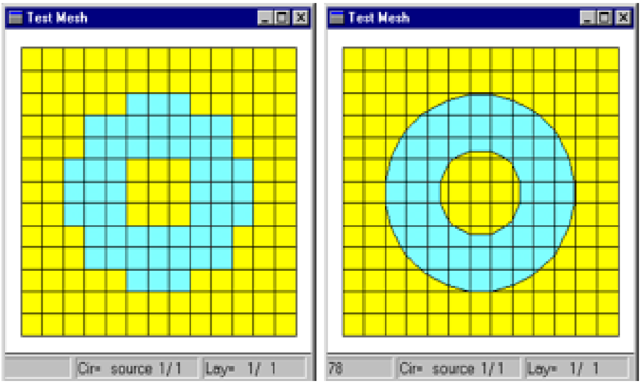
$$ {}_{k,l,m+0.5}E_z^{n+1} = E_z^n + \frac{\Delta t}{{}_{k,l,m+0.5}\varepsilon_z \varepsilon_0} \cdot \left\{ \left[{}_{k+0.5,l,m+0.5}H_y^{n+0.5} - {}_{k-0.5,l,m+0.5}H_y^{n+0.5} \right] \frac{1}{\Delta x} + \left[{}_{k,l-0.5,m+0.5}H_x^{n+0.5} - {}_{k,l+0.5,m+0.5}H_x^{n+0.5} \right] \frac{1}{\Delta y} \right\} $$

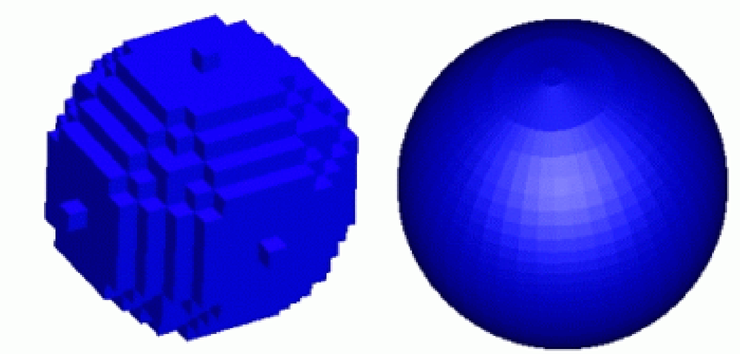
"Keep an eye on this one, it promises to be a gem",

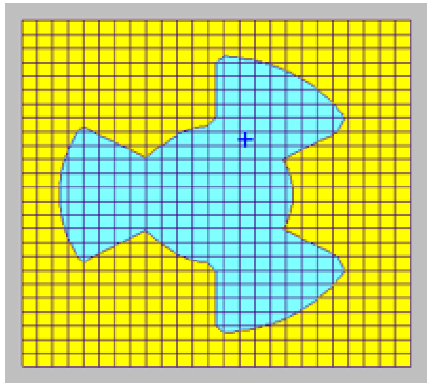
Mark Mirotznik,
IEEE Spectrum April 1998

We discretise time and space (in a conformal manner).



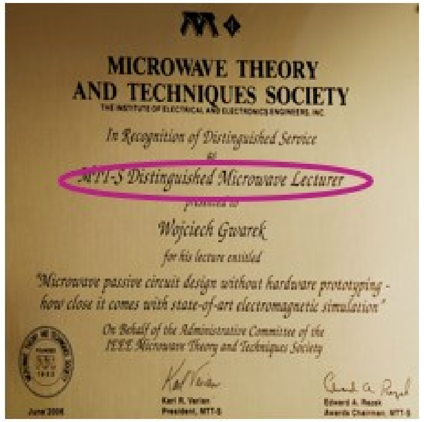






Modeling of MW Heating: Recognition

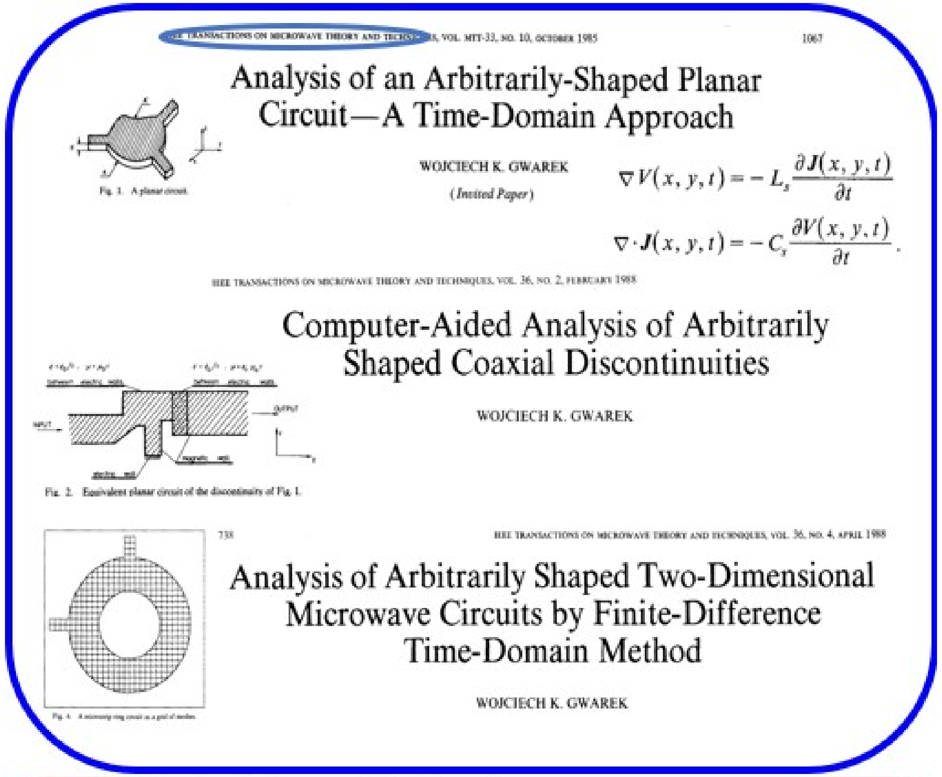
IEEE- awarded research of Prof. Wojciech Gwarek, QWED's co-founder (1997) & 1st President (till 2017)

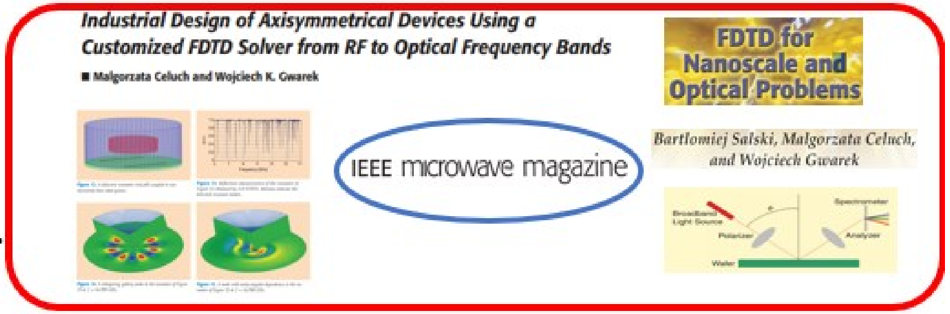


New conformal FDTD method:

+ Conformal Space Discretisation
(similar to FEM - arbitrary shapes).

+ Time-Domain Solution
(faster than FEM - wide frequency band, diagonal mass matrices).





From EM to Multiphysics Modeling

The time-domain approach allows us
to dynamically and naturally modify during the heating:

- positions of objects,
- material parameters of heated objects,
- excitation (e.g.solid-state computer-controlled sources).

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

↑

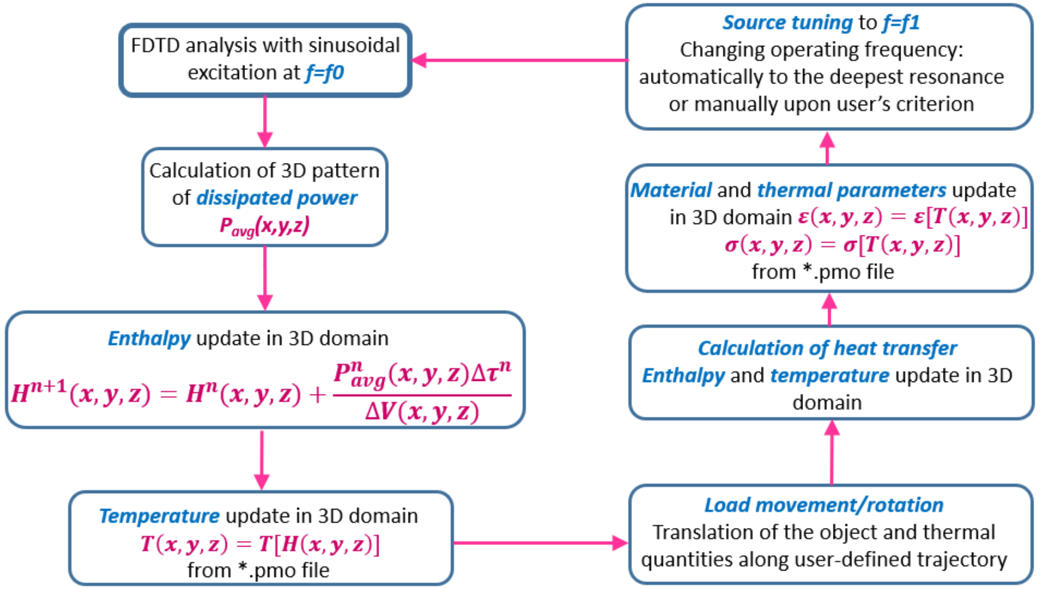
Material and ***thermal parameters*** update in 3D domain $\varepsilon(x,y,z) = \varepsilon[T(x,y,z)]$
$\sigma(x,y,z) = \sigma[T(x,y,z)]$
from *.pmo file

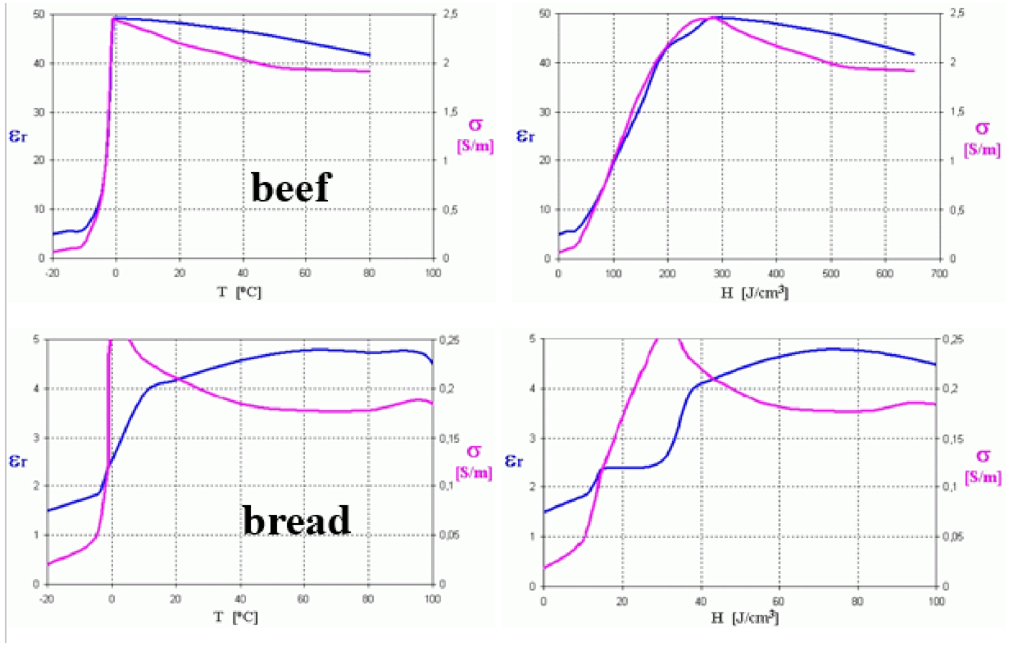
↑

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

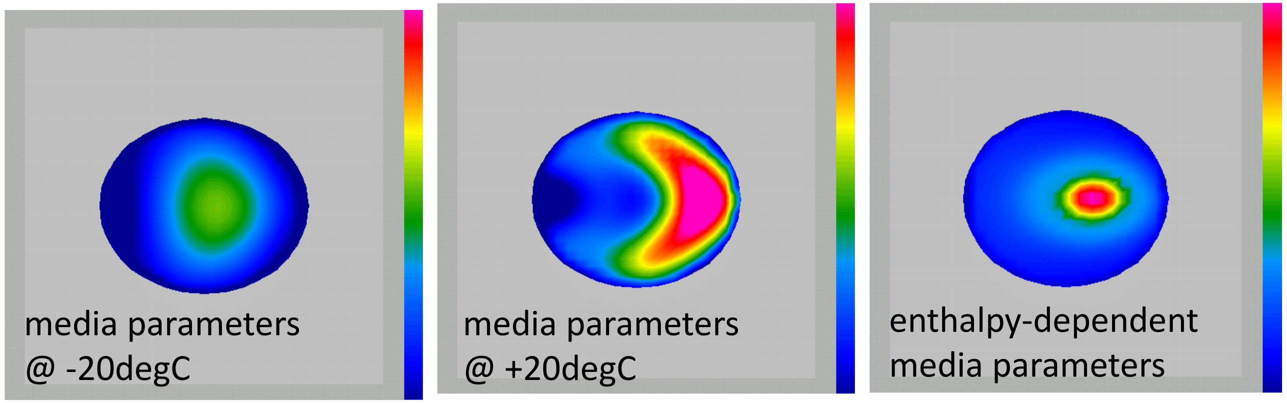
→ (back to FDTD analysis)

Example: Thermally-Dependent Foods





materials' data courtesy P.O.Risman



QuickWave™ Software Overview

Advanced Electromagnetic & Mutliphysics Simulation Software for Industrial and Research Applications

Key modules & functionalities:

Full 3D EM solver with a range of unique models.

Vector 2D (BoR), **ultra fast** solver applicable to the analysis of **axisymmetrical** devices. Almost instantaneous convergence!

BHM Heat Module, **heating analysis** including loads rotation and translation, frequency tuning, **heat flow** and material parameters modification.

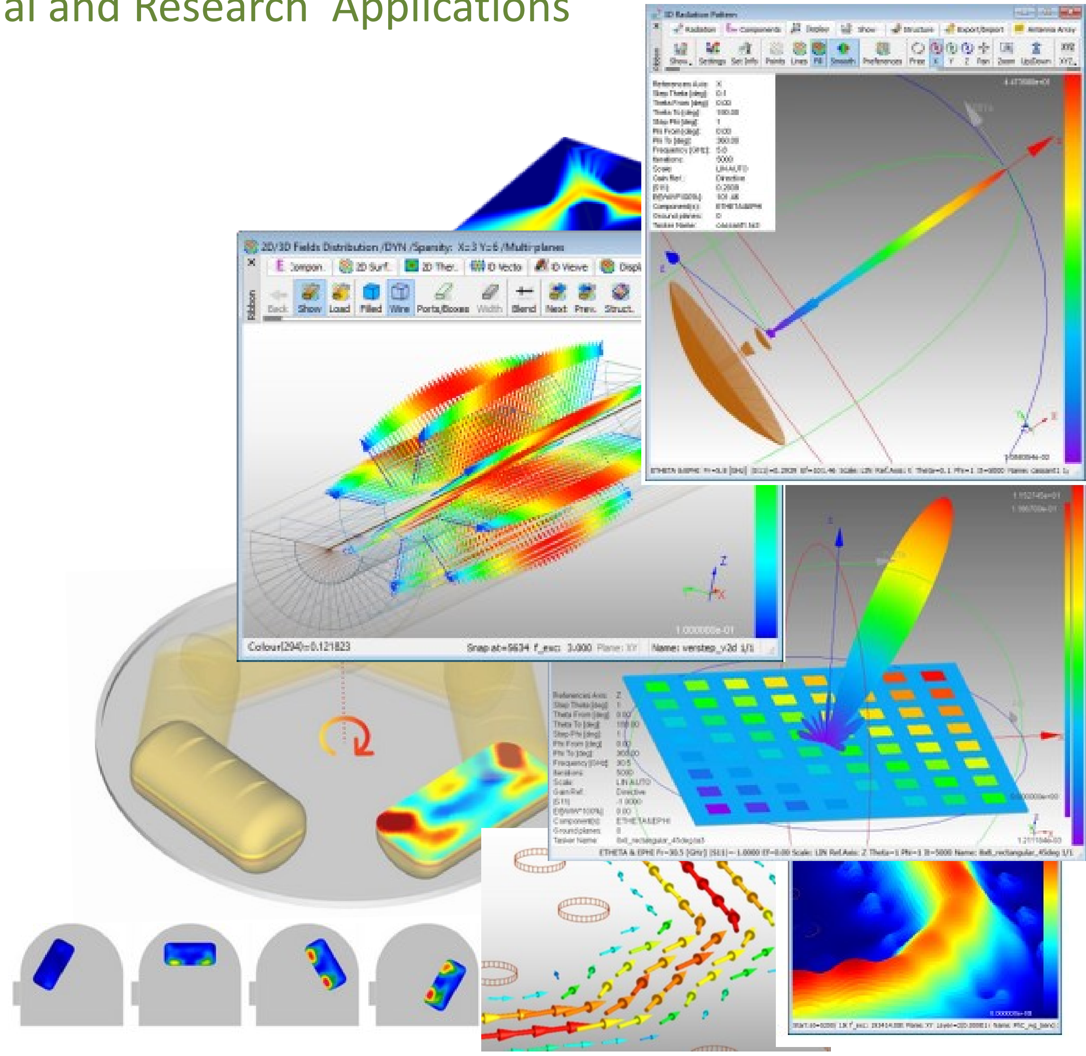
QProny module for high Q-factor structures analysis.

OptimiserPlus multiobjective optimiser which allows to finding an optimal solution in an automatic way.

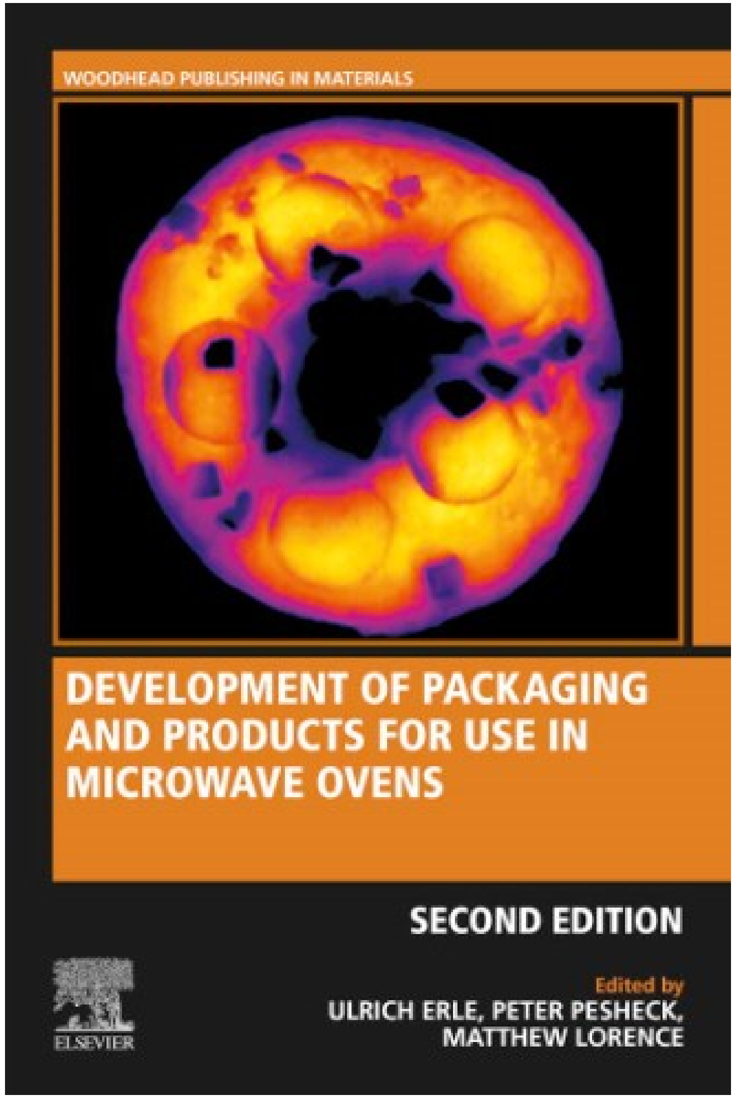
Multiprocessor/multicore and **MultiGPU** computing ensures **maximum** performance of your computer's resources

QW-AddIn for Autodesk® Inventor® Software

and more...



Benchmarking & Applications

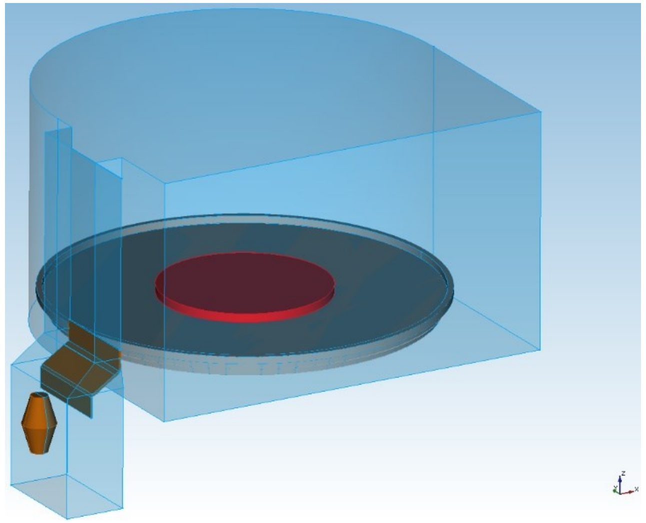


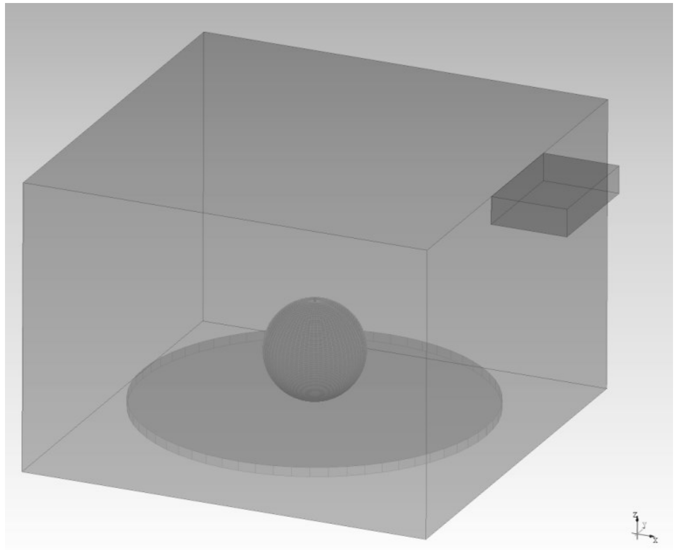
We focus on two modeling scenarios ("Elsevier MW Book" 2020):

1. a simple representative oven (Risman, Microwave World, 1998)

2. a complex commercial Whirlpool Max oven.

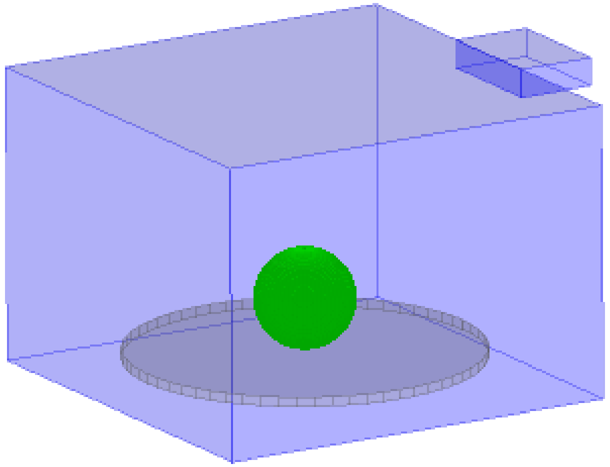
QWED team contributed 3 chapters.





A Simple Benchmark (1)

[2] 



QuickWave v2022 (FDTD)

Intel Core i7-8700 3.2 GHz, 6 Core(s)

RAM: 16 GB

Graphic Card: AMD Radeon Pro WX 3100

Microwave Oven Parameters

The oven has:

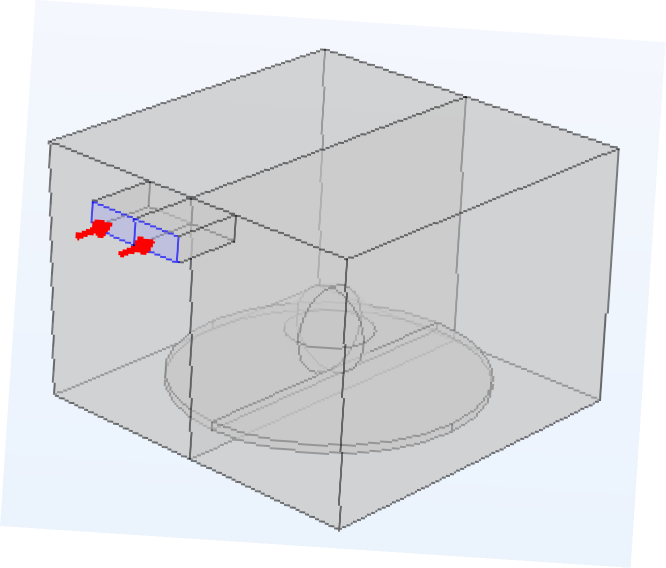
- a width of 267 mm,
- a depth of 270 mm,
- a height of 188 mm.

The waveguide's dimensions are:

- 50 mm in width,
- 78 mm in depth,
- and 18 mm in height.

The glass plate has:

- a radius of 113.5 mm,
- a height of 6 mm,
- and a base of 15 mm.



COMSOL Multiphysics 5.6 (FEM)

Intel i7-3820 CPU @ 3.6 GHz, 4 Core(s)

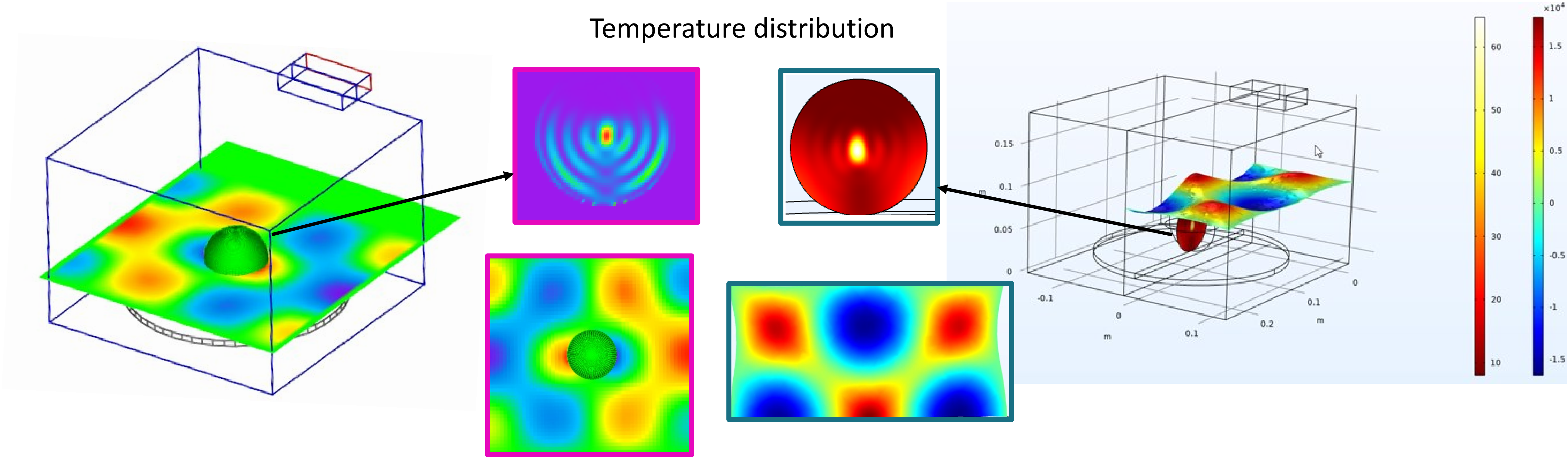
RAM: 64 GB

Graphic Card: NVIDIA GeForce GTX 660 Ti

The potato has a radius of 31.5 mm and its initial temperature is **8°C**.
Relative permittivity of potato is equal to **65** and its conductivity to **2.722 S/m**.

A Simple Benchmark (2)

Temperature distribution



Electric field distribution

QuickWave v2022 (FDTD)

Simulation time: 00:00:42 (h:min:sec)

COMSOL Multiphysics 5.6 (FEM)

Simulation time: 00:01:05 (h:min:sec)

A Simple Benchmark (3)

Simulation info

For both methods, a Frequency step of **0.001 GHz** was chosen.

COMSOL Multiphysics 5.6 (FEM)

Simulation time: 01:04:12 (h:min:sec)

RAM: 4220 MB

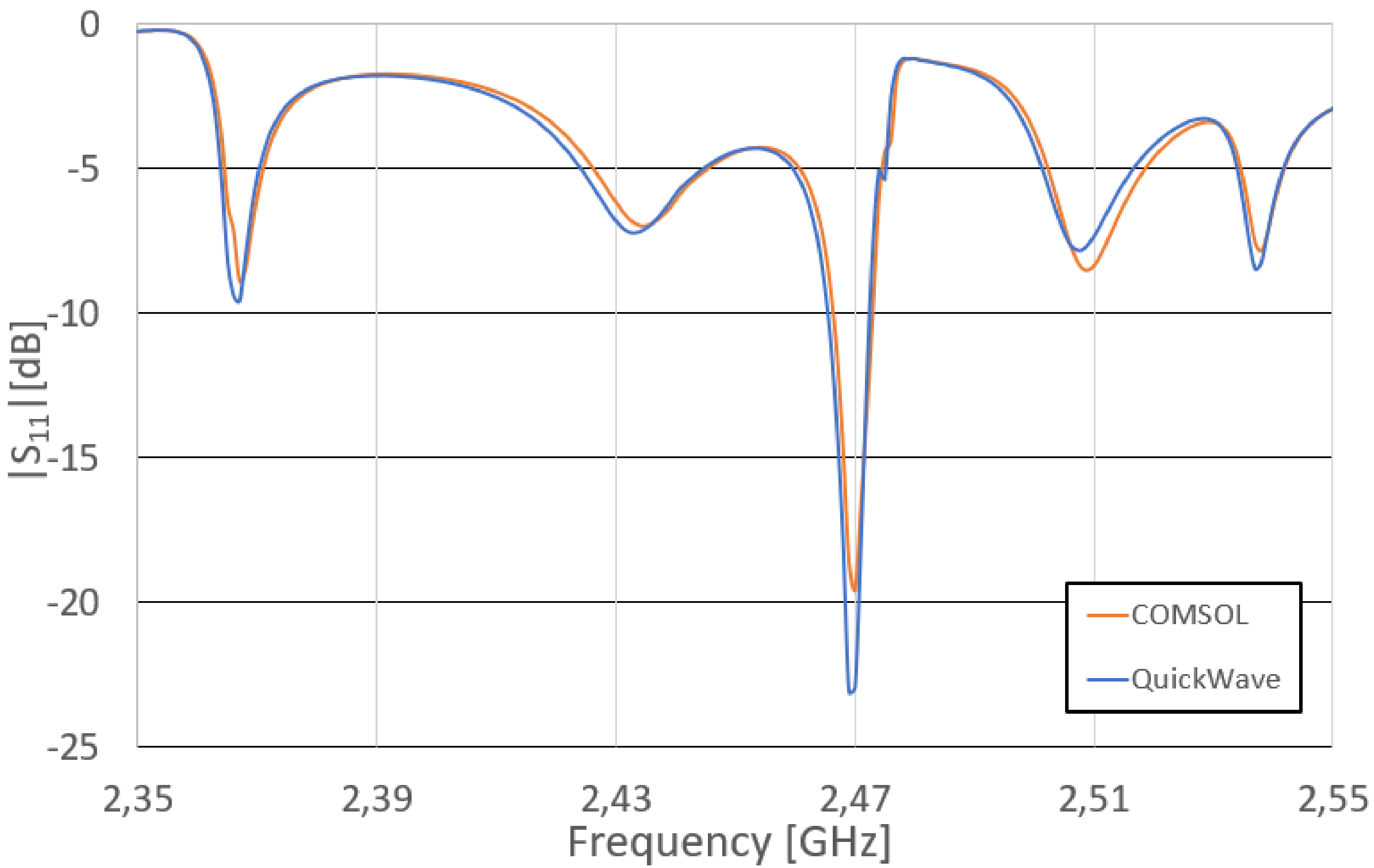
Cells: 60 004

QuickWave v2022 (FDTD)

Simulation time: 00:05:03 (h:min:sec)

RAM: 364 MB

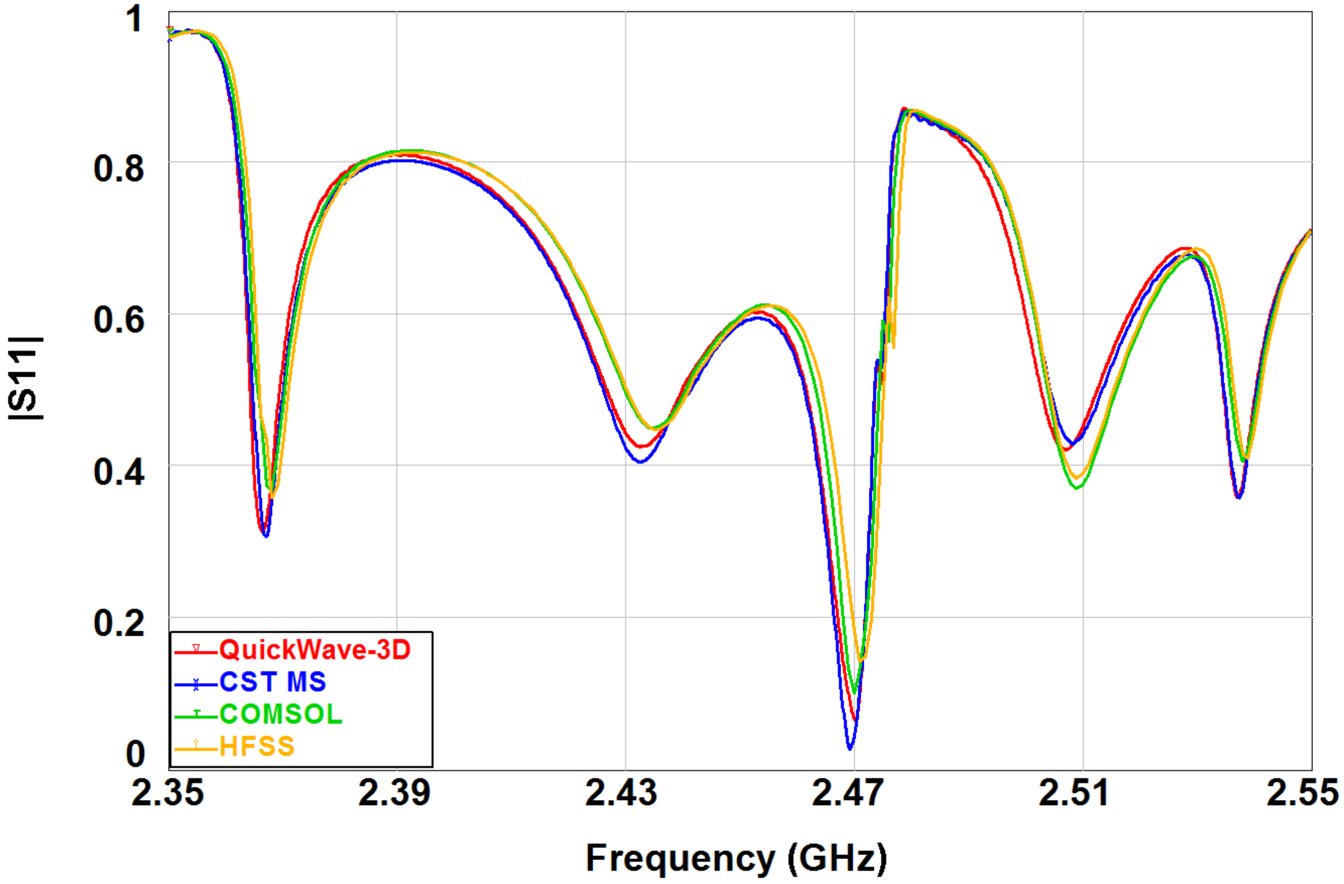
Cells: 3 614 128



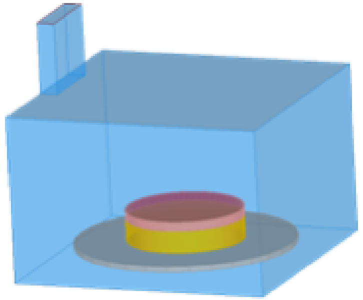
A Simple Benchmark (4)

	Computation time[a]	Element/cell count	RAM usage
QuickWave-3D	3 min 43 s	3 602 463	217 MB (GPU memory for scenario) 288 MB (RAM for exe)
CST MS	5 min 44 s	4 591 720	2194 MB (peak memory reported in log)
COMSOL	25 min 20 s	60 004	3300 MB
ANSYS HFSS v19.2	43 min 53 s	24 014	2168 MB

[a] The calculations were performed with the most optimum acceleration regime available for each software licence. For FDTD based software, GPU acceleration (on Nvidia GeForce GTX Titan for QuickWave-3D and Tesla K40c for CST MS) was adopted, and for FEM based solvers, multicore computations (on AMD Ryzen 7 1800x and Intel i7-3930K processors for COMSOL and ANSYS HFSS, respectively) were performed.



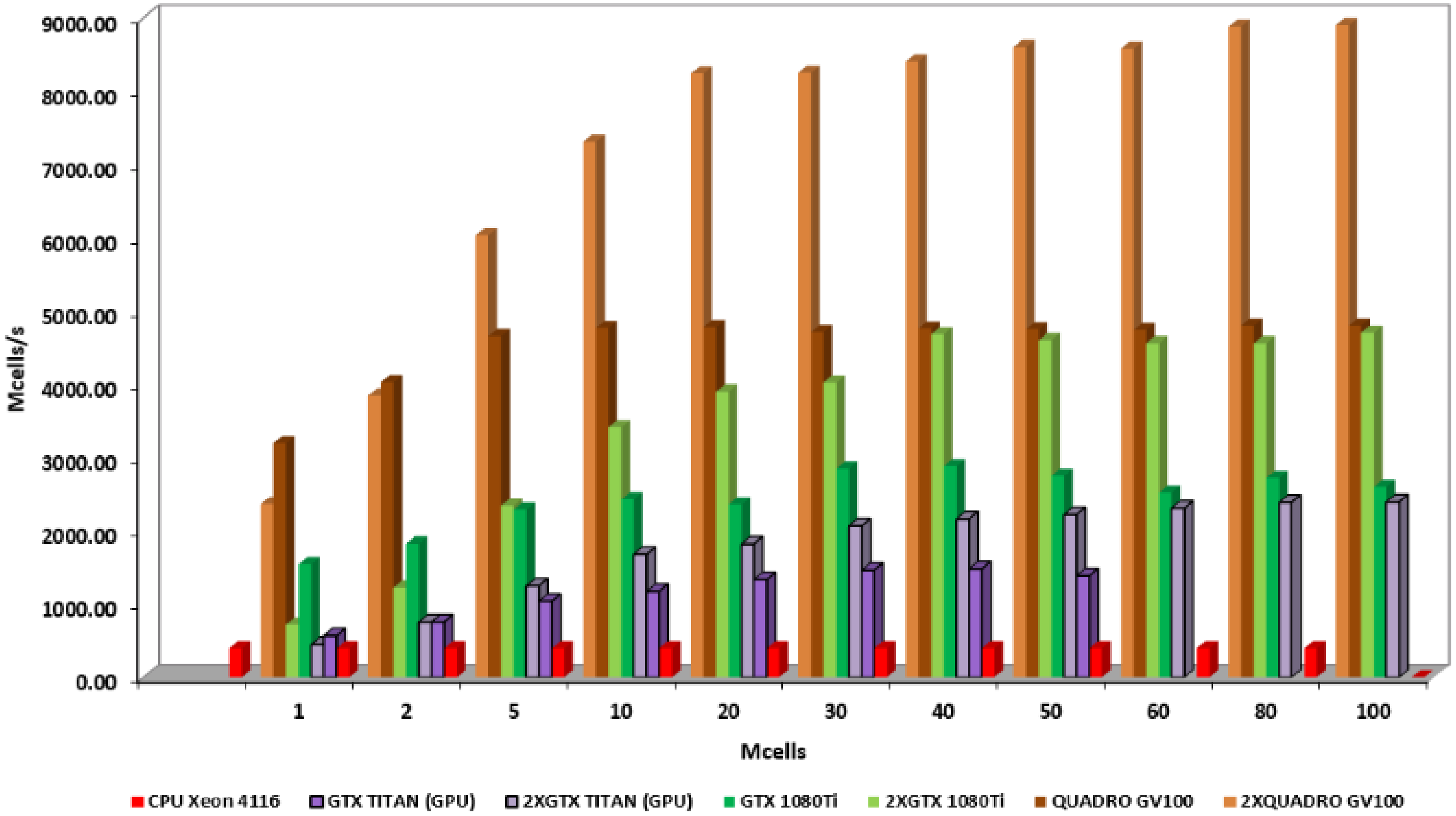
Note on Hardware Acceleration



Popular hardware acceleration options include:

1. moving from CPU to GPU
2. dividing the computation region into subregions, simulated on separate processors.

A comination of both options – MultiGPU – is especially powerful.



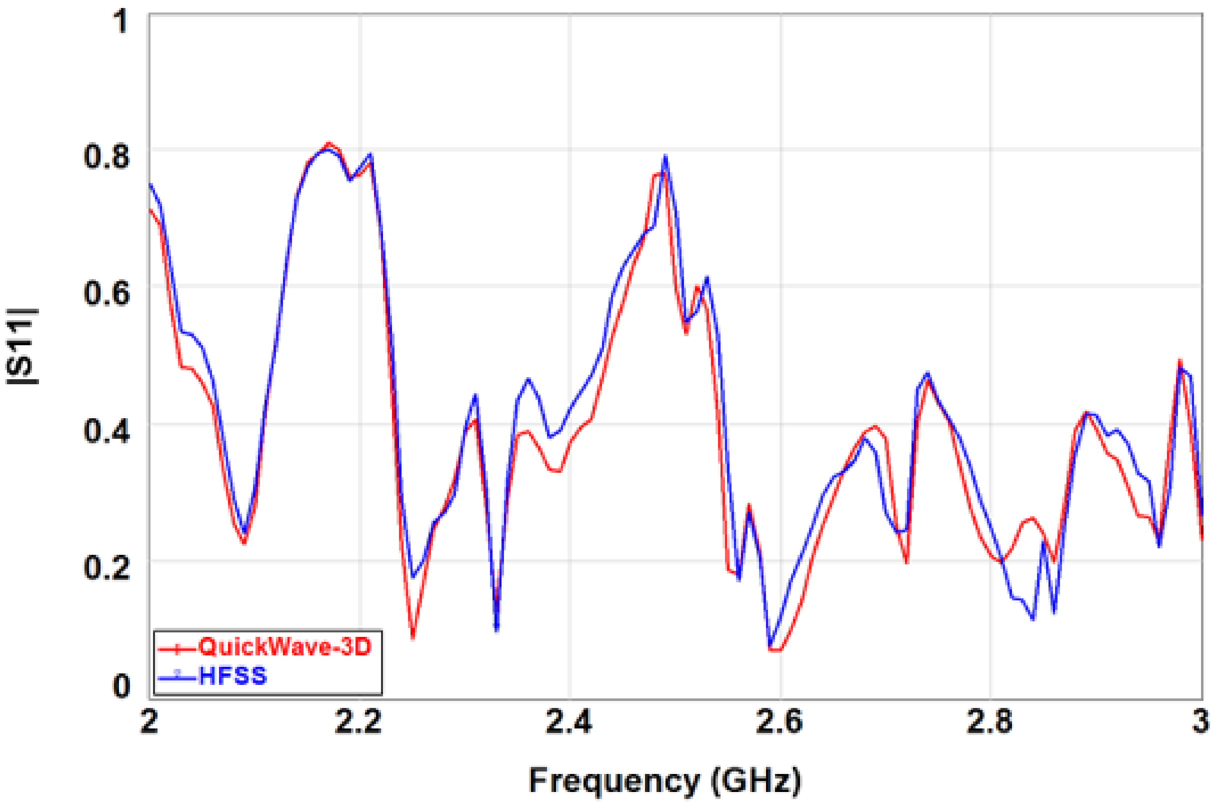
SpeedUp of the GPU and MultiGPU simulation scenario (project divided along Y direction into two symmetrical subregions) computation of a beefburger placed in a cavity oven (3D example) compared to QW-OMP version on Xeon 4116.

Quadro GV100 cards have been provided by Servodata Elektronik Sp. z o.o., Poland

Max Oven - EM Model (1)

	Computation time[a]	Element/cell count	RAM usage
QuickWave-3D v2018	1 min 18s	1 422 900	86 MB (GPU memory for scenario) 319 MB (RAM for exe)
ANSYS HFSS v19.2	29 min 3s	35 407	2844 MB (peak memory reported in log)
QuickWave v7.0	39 min 17s	1 323 120	136 MB
HFSS v11	300 min 8s	31 000	955 MB

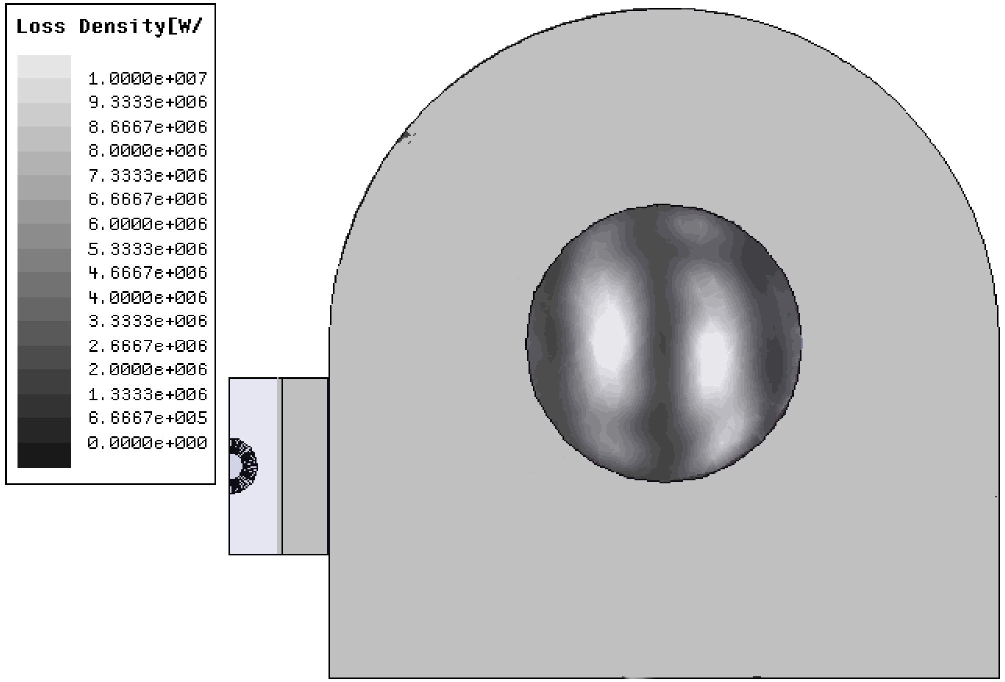
[a] The calculations were performed with the most optimum acceleration regime available for each software licence. For FDTD based software GPU acceleration (on Nvidia GeForce GTX Titan) was adopted, and for FEM based solvers, multicore computations (on Intel i7-3930K processor) were performed. For QuickWave v7.0 and HFSS v11, calculations were performed on 2.21 GHz AMD Athlon 3500+ and 2.4 GHz Intel Pentium IV platform respectively.



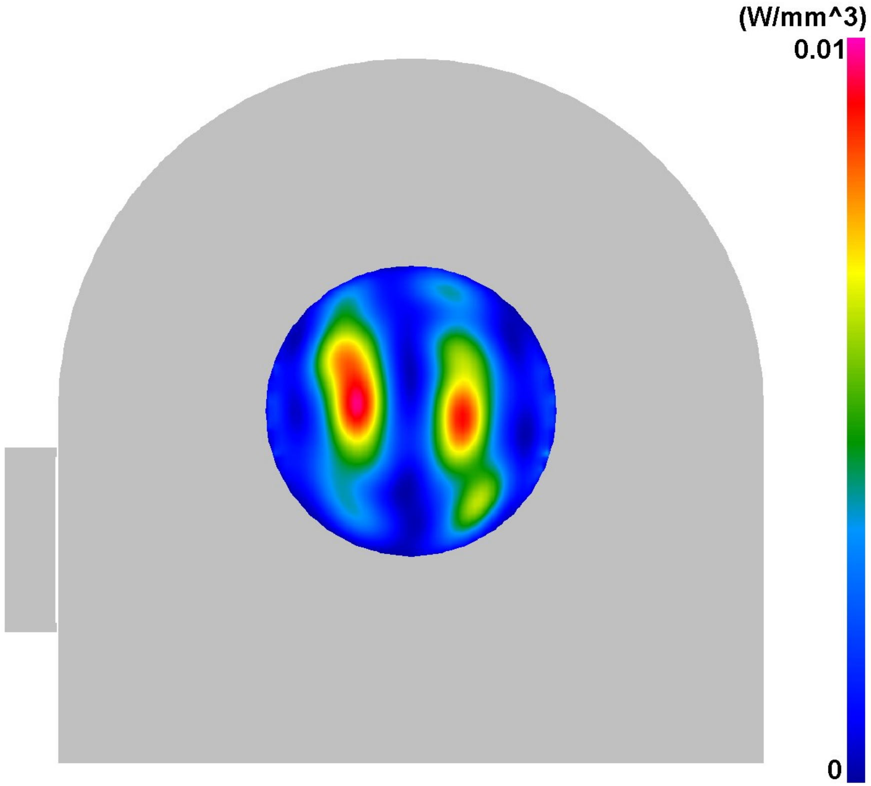
Max Oven – EM Model (2)

Dissipated power density distribution in the cross-section of the load heated from in Whirlpool Max.

HFSS package v11 (values given in W/m³)



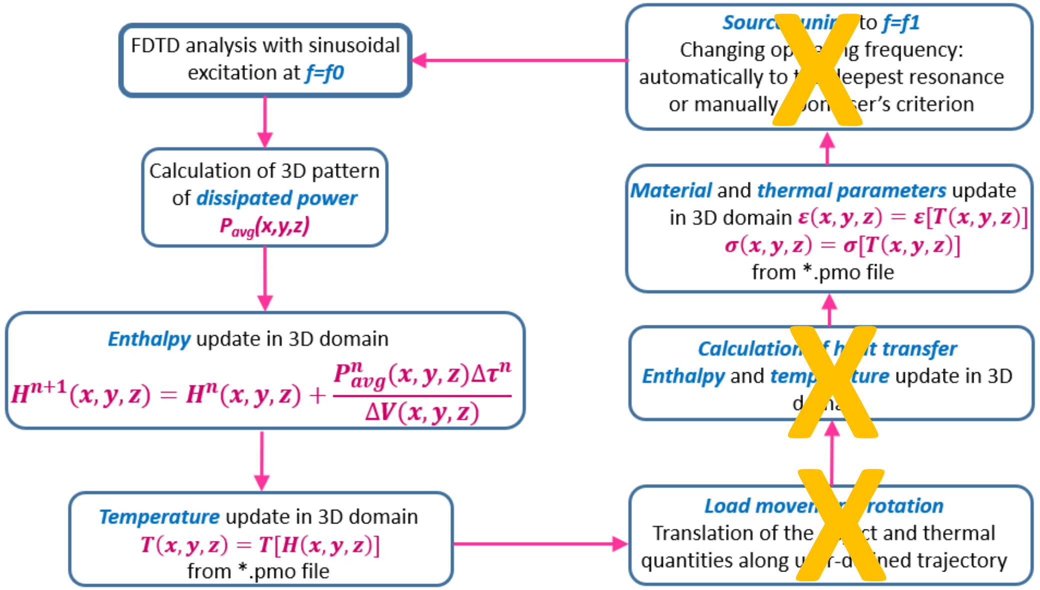
QuickWave-3D v2018 package (values given in W/mm³)

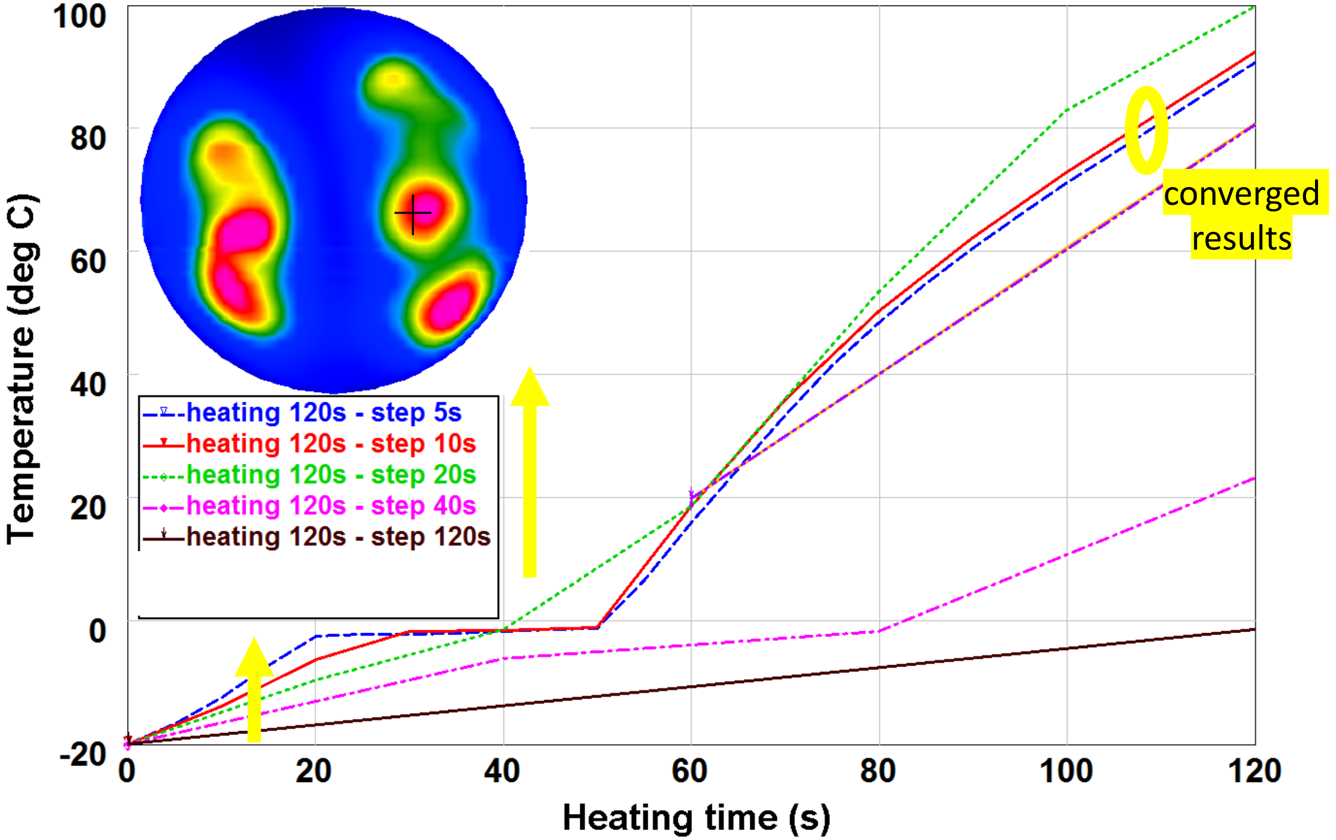


Max Oven – Multiphysics Model (1)

Thermally dependent load parameters – effect of parameterisation of the nonlinear heating process

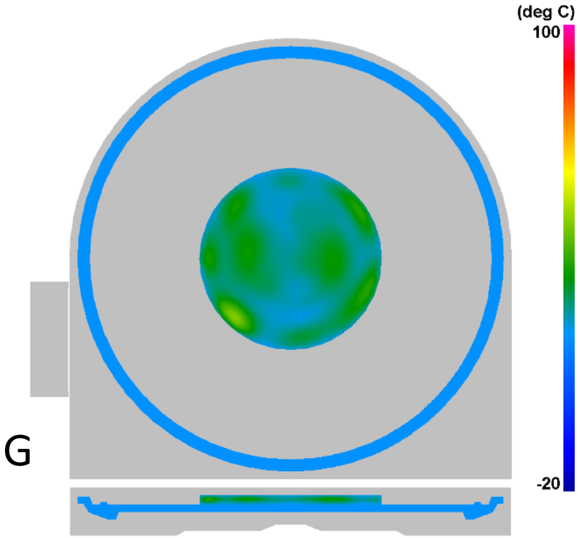
- same total heating time
- increased number of "thermal" computational iterations, at which material parameters are automatically updated based on current temperature reached in a given FDTD cell

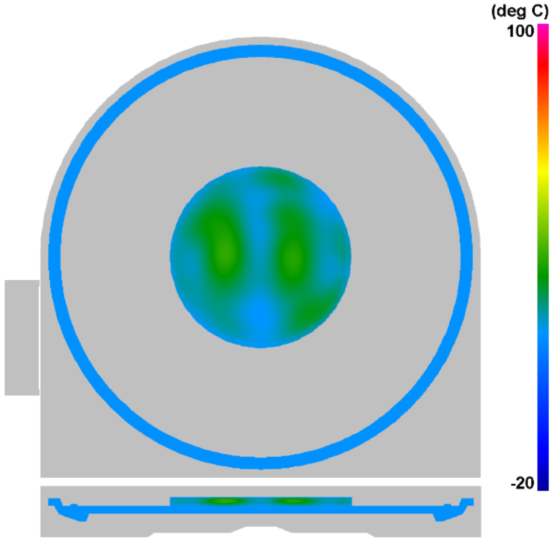




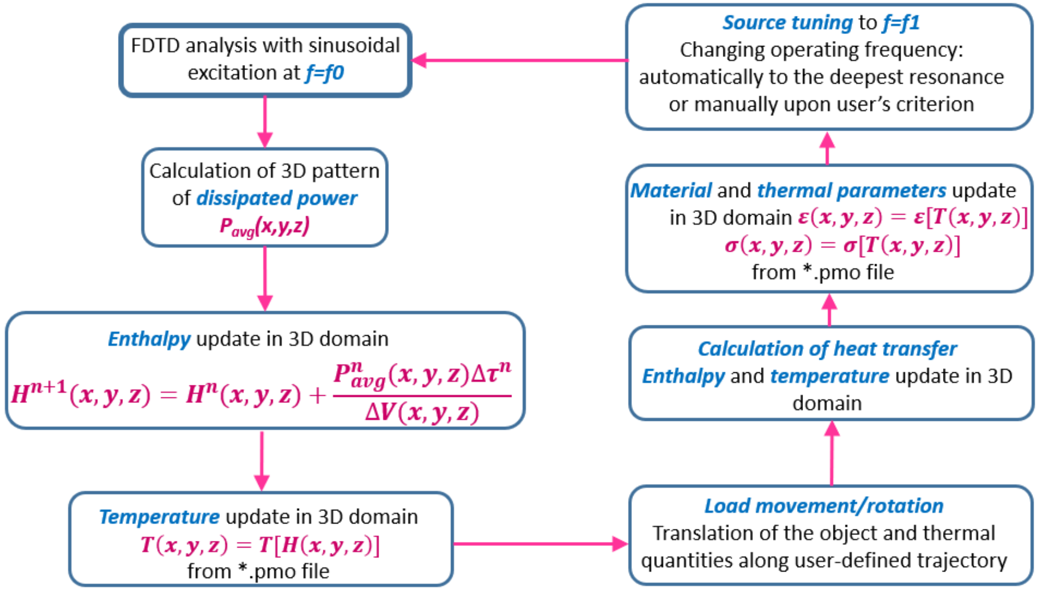
Max Oven – Multiphysics Model (2)

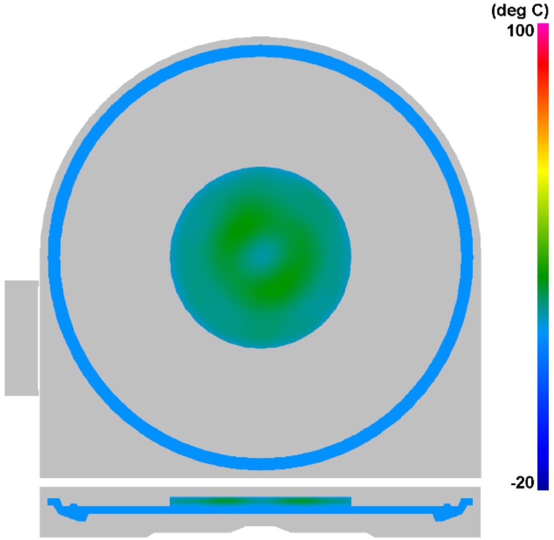
HEAT FLOW +
MAGNETRON PULLING





HEAT FLOW

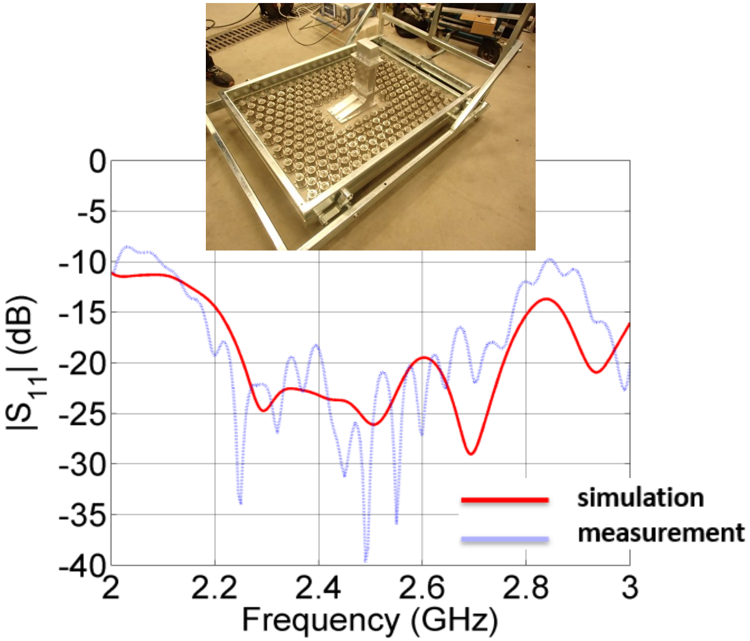


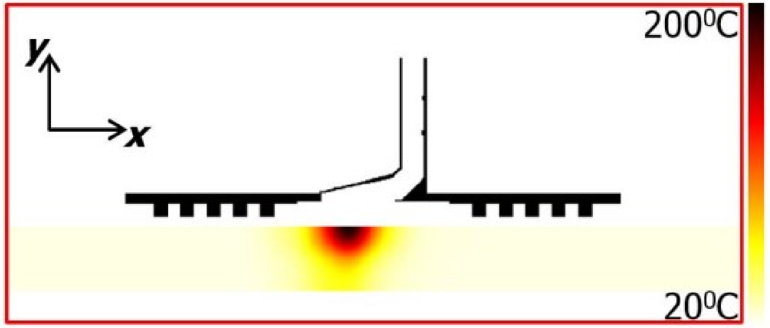


HEAT FLOW +
LOAD ROTATION

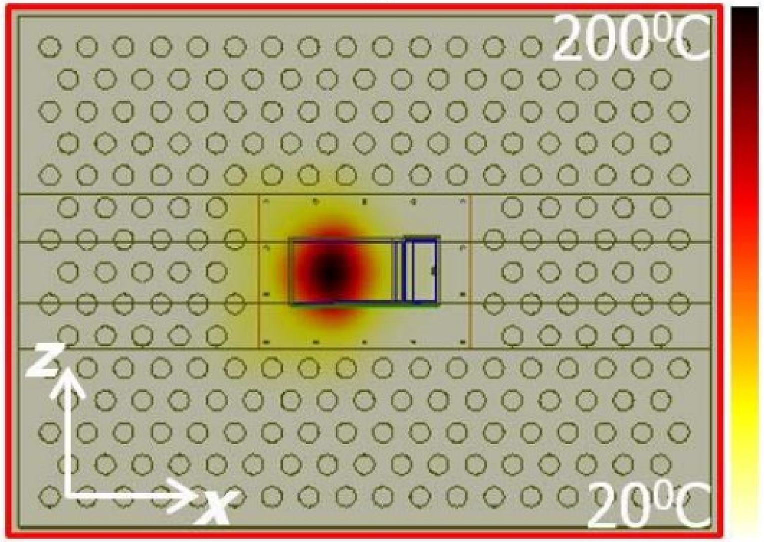
Note on "Real" Problem Size

Example: applicator for heating bituminous surfaces (with a safety system including chokes to block leakage)

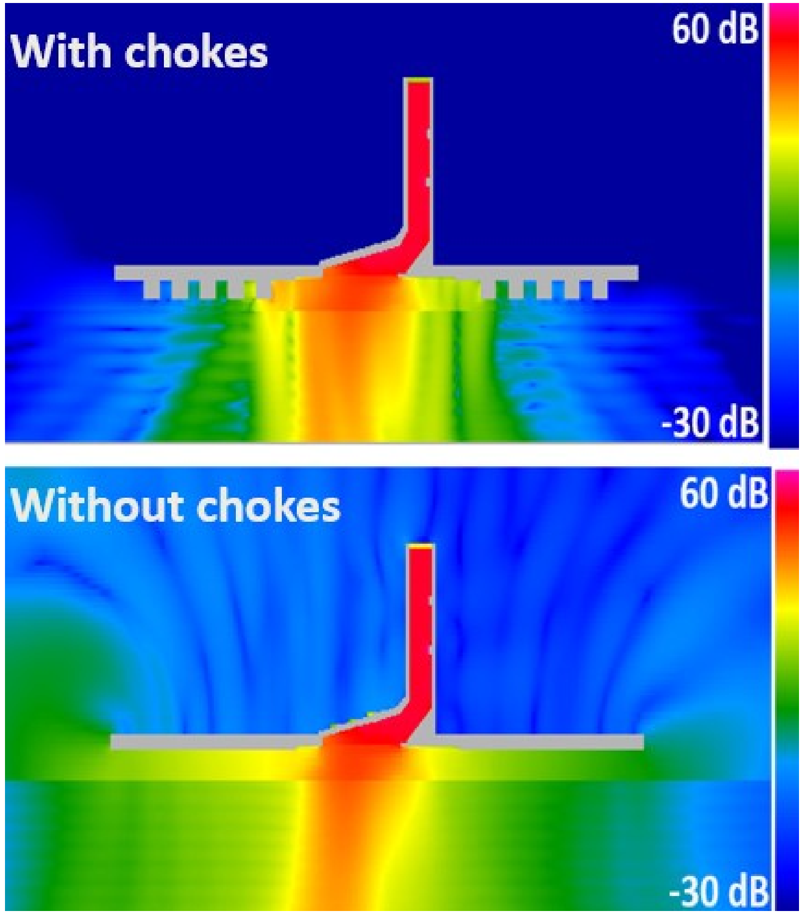




(a)



(b)



FDTD cell size ≥ 1.3mm
Problem size: several wavelength

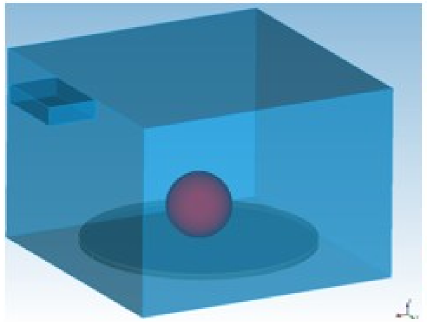
FDTD model of 9.4 million cells
RAM: 779 MB

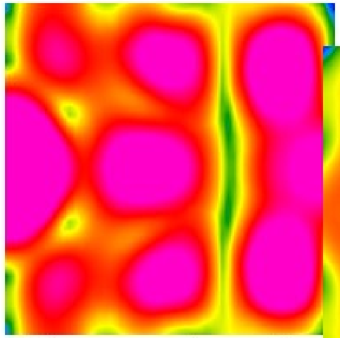
Simulation time: 26 seconds

FDTD is particularly advantageous for problems "big" wrt to wavelength, which are too big for running FEM simulations on available computers

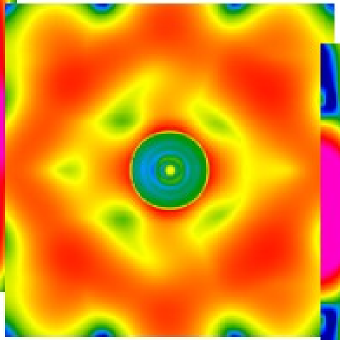
NEW: New-Field Imaging Function

Separation of incident and diffracted fields for biomedical research applications (*request of P.O.Risman, Malardalen Univesity*)

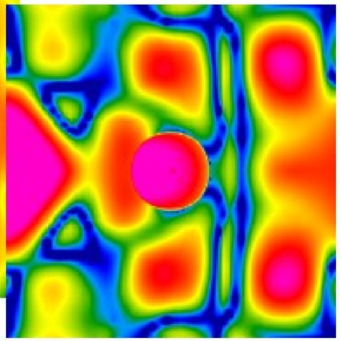




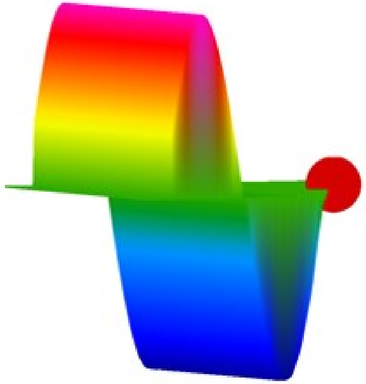
E-field in an empty cavity

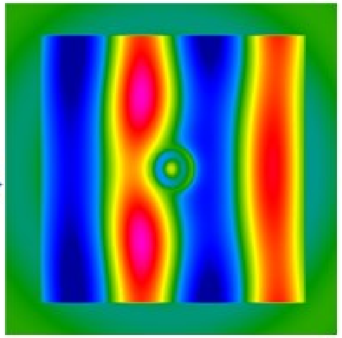


E-field in a loaded cavity

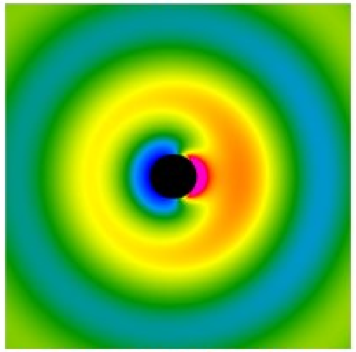


Scattered near-filed in cavity



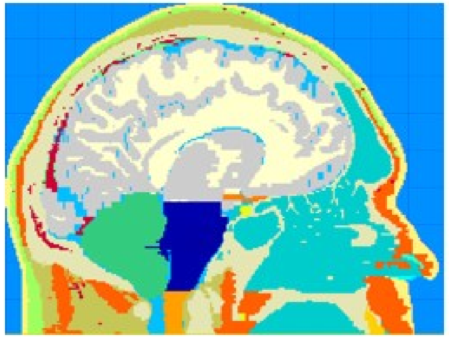


Total field
Focusing by the load
„exploding egg effect"

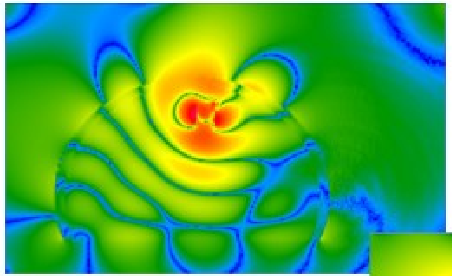


Diffracted field reveals cause of focusing: circumferential resonance

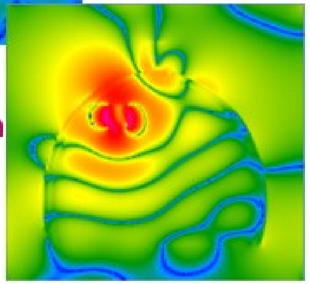
Detection of inhomogenities in tissues



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



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



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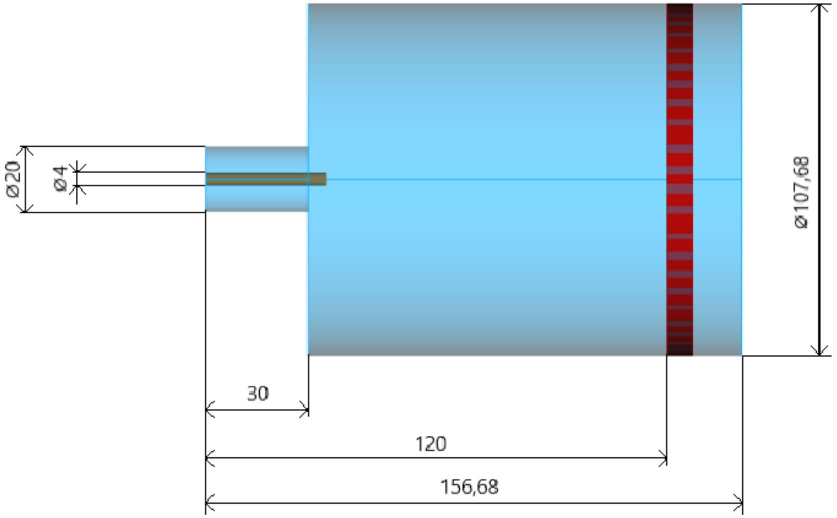
* https://sites.utexas.edu/austinmanaustinwomanmodels/

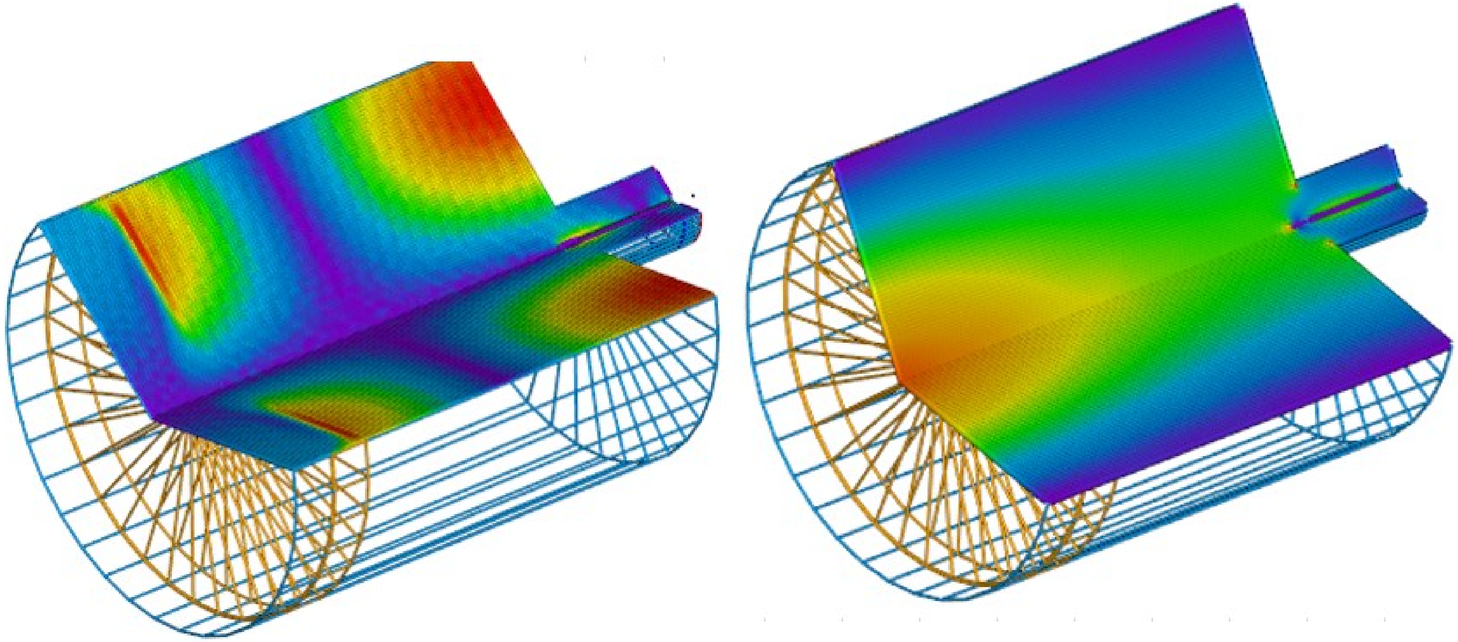
New:
Multiphysics Modeling of BoR Scenarios (1)



Microwave Applicator dimensions [3]

•The TE_{110} mode cannot exist in the resonator; the lower mode of the TE family is TE_{111}, and its eigenfrequency depends on the length of the resonator.

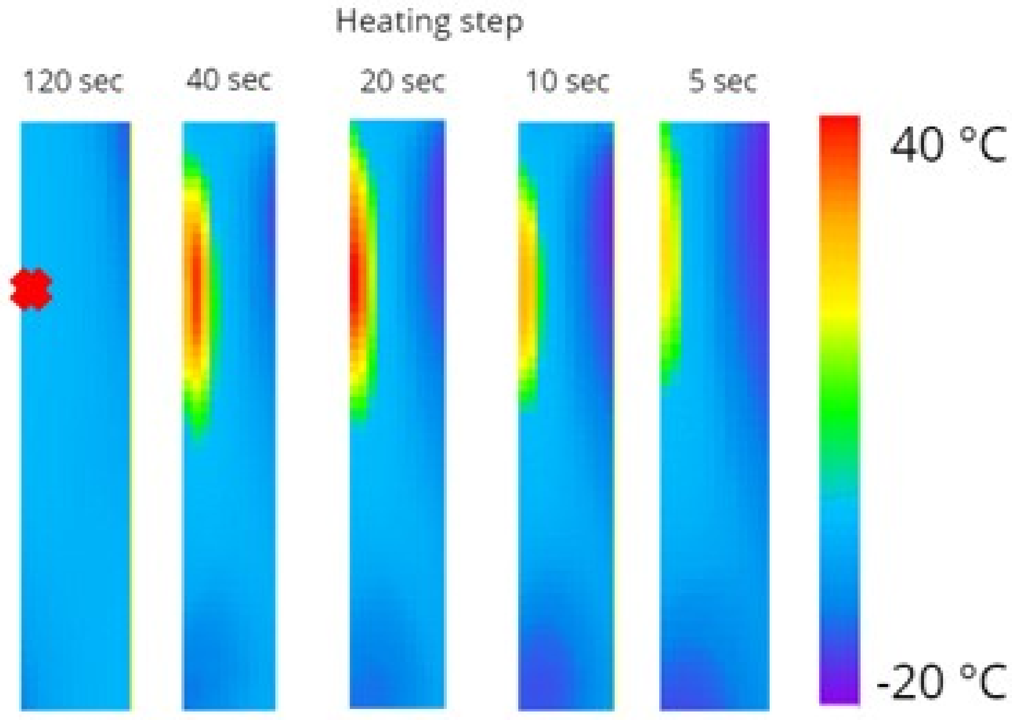
•Microwave heating applicators that support TM modes can use both electric field components - normal and tangential to a flat load placed in parallel to the resonator's bottom and cover.



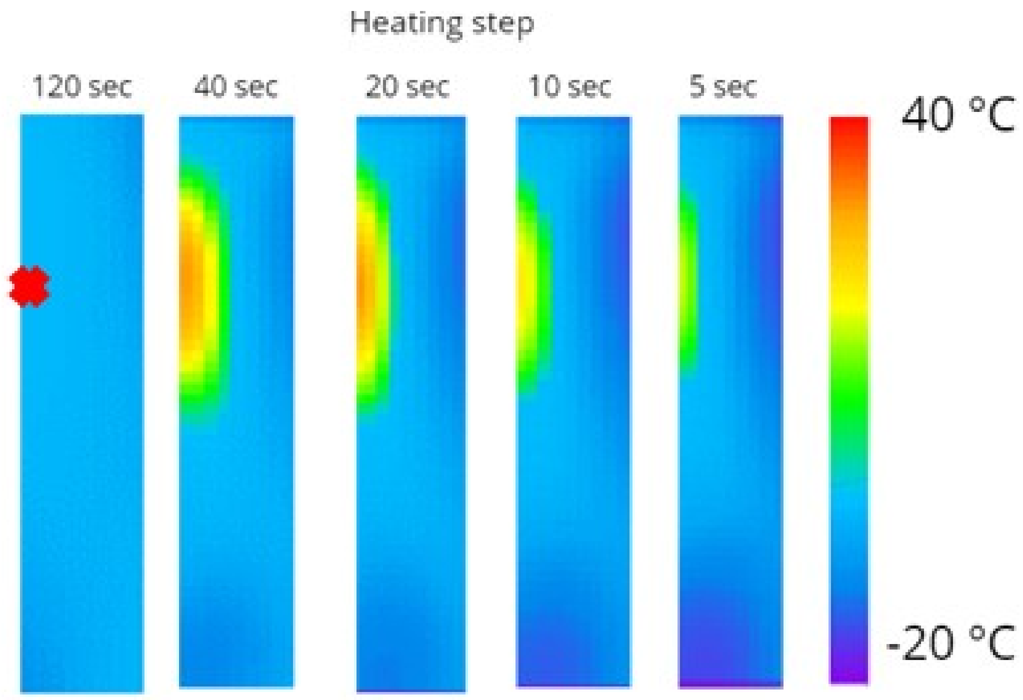
Distribution of the angular magnetic field and electric field of the TM_{011} mode, in a 270 degree view of the cylinder.

Multiphysics Modeling of BoR Scenario (4)

- Beef case



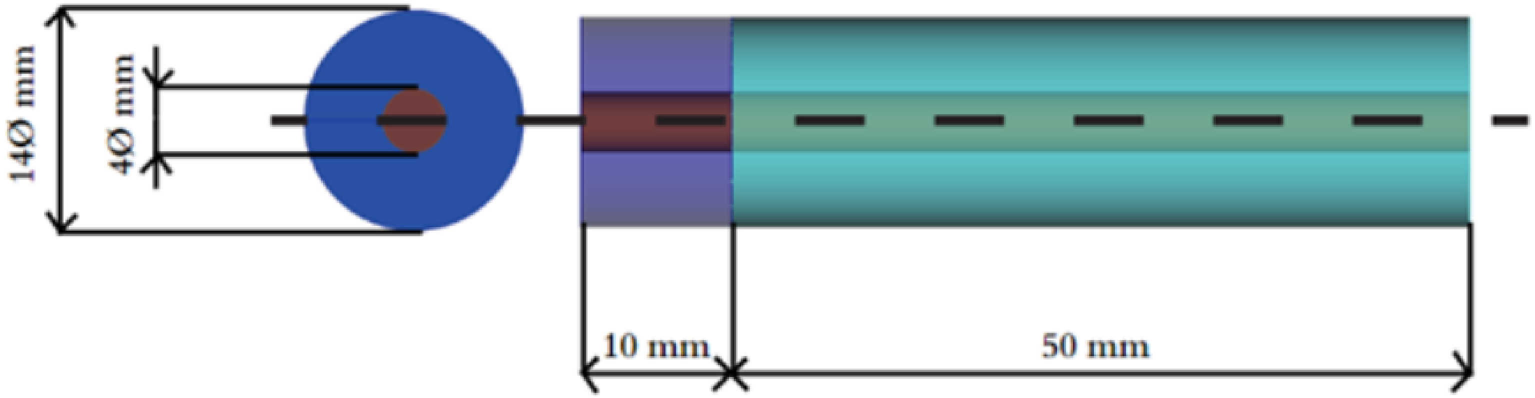
Distribution of final temperature in beef after heating for 120 seconds **(heat flow neglected)** - parameterised simulations using different heating steps.



Distribution of final temperature in beef after heating for 120 seconds, **including heat flow** phenomenon – parameterised simulations using different heating steps.

New: Application to Batteries (1)

Nano Bat



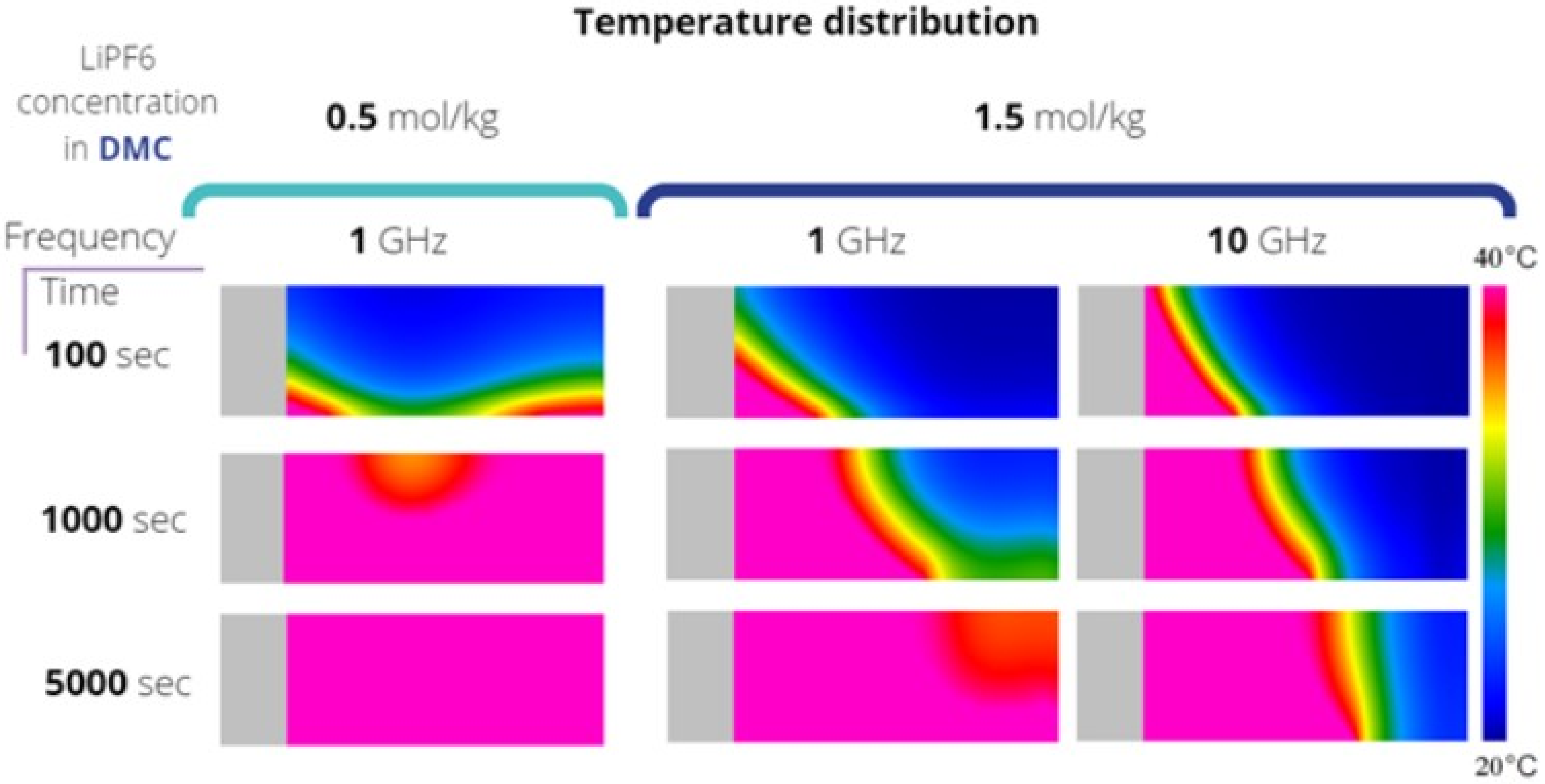
The battery being considered has a collector at its center, which acts as a perfect electric conductor (PEC) in the simulation. At the starting point of the system lies a source that is excited at a sinusoidal frequency of **1 or 10 GHz**. A 10 mm air separator is also present, with its reference plane situated in the middle. Following this is the electrolyte, which is a lossy material that terminates with a special symmetrical boundary condition of magnetic type design known as a perfect magnetic conductor (PMC).

Temperature [°C]	LiPF6 concentration* [mol/kg] 0.5	1.5	Specific Heat capacity** [J/g°C]	Density* [g/cm³]	Dielectric Constant* [F/m]
	Conductivity* [S/m]				
0	0.2	0.58	1.704	1.063	3.1075
10		0.65			
20		0.82			
30		1.04			
40		1.52			

*E. R. Logan *et al* 2018 *J. Electrochem. Soc.* **165** A705

** Zhou, Y. , Wu, J. and Lemmon, E. (2011), Thermodynamic Properties of Dimethyl Carbonate, J. Phys. & Chem. Ref. Data (JPCRD), National Institute of Standards and Technology, Gaithersburg

New: Application to Batteries (2)

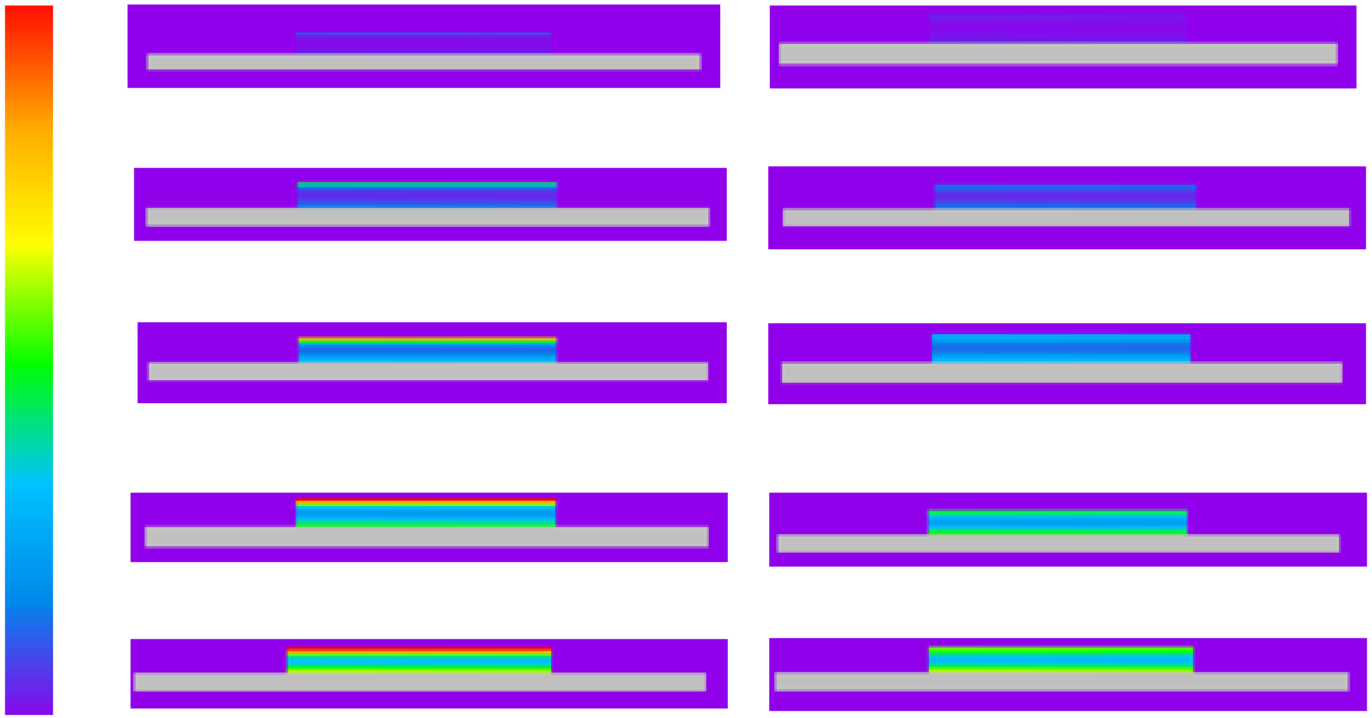


New: EM+Thermal + Radiation Model

- Beef case

80 °C

Heat Flow with radiation | Heat Flow without radiation | Heating Time



20 °C

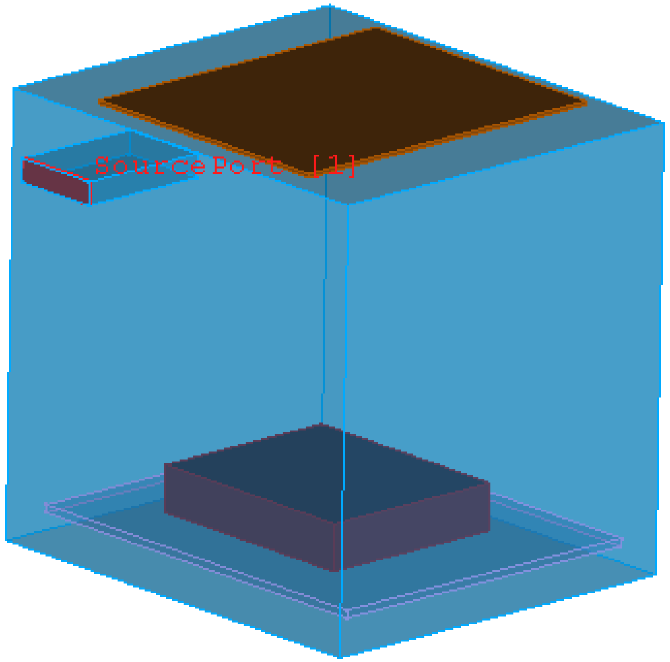
1 second

5 seconds

10 seconds

15 seconds

20 seconds



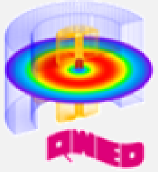
Exploring Synergies between Computer Modeling & Material Measurements

Commercial since 1997
QuickWave Simulation Software
~1000 licences implemented

THE EUROPEAN ICT PRIZE WINNER

Modelling (EM, MW, multiphysics,...)
- waves in free space is "easy" Maxwellian
- wave interaction with matter is "complicated"...

INNOVATION

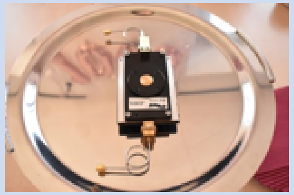


Applicator design & model for parameter extraction

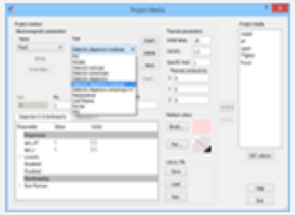
Material measurements

Commercial resonator test-fixtures since 2001

1000th unit sold in 2020



Accurate material parameters (constitutive relations)



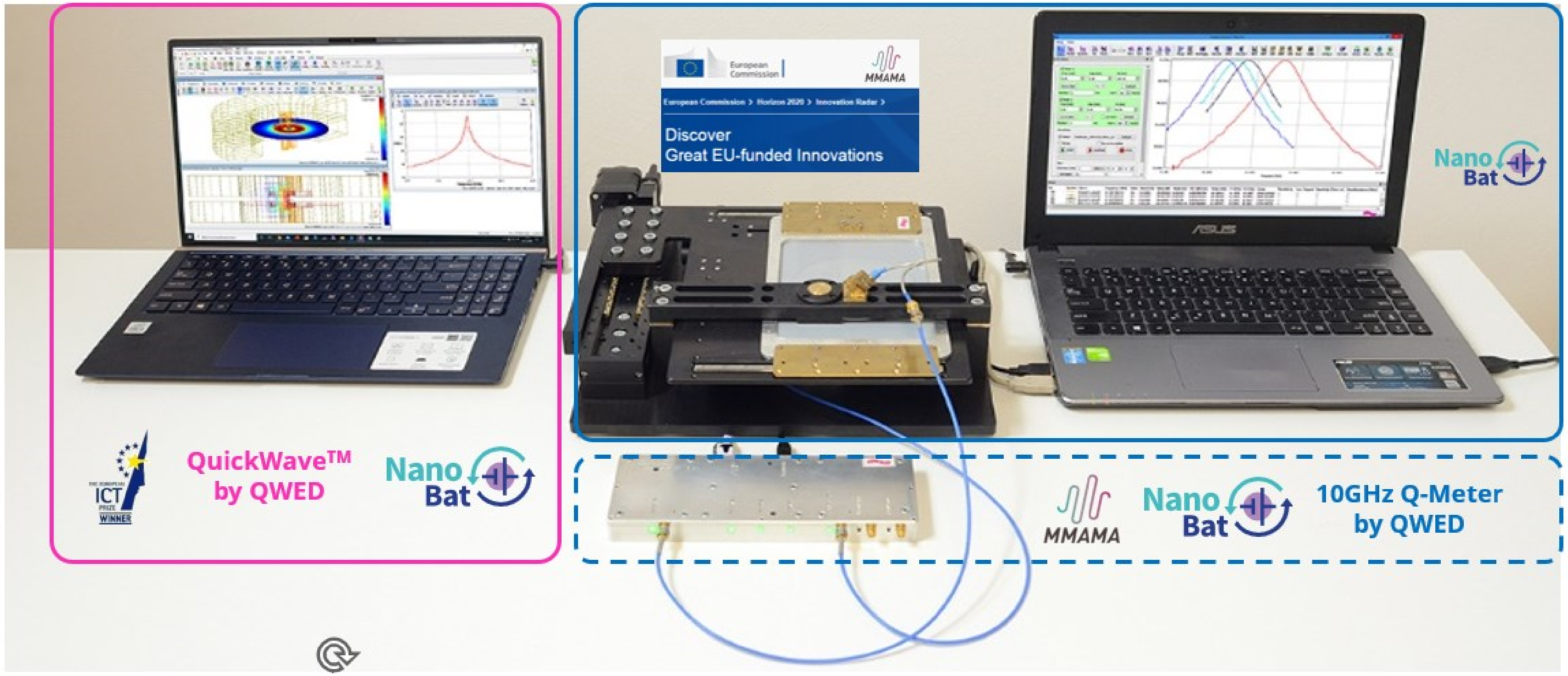
Open Platform Examples & Tools

QW-Modeller for QuickWave
Free general purpose 3D CAD modeller for QuickWave

Open Platform Examples:
SMM tip presented at Numerical Electromagnetic

European Standard:
IEC 61189-2-721:2015
CEN-CENELEC Workshop 2021

Example of
Twinned Modeling + Characterisation



- Originally designed for organic semiconductors (for solar cells)
- Widely used for various electronic materials (high-resistivity)
- Applicable to food packaging, glass, other materials relevant to MW heating systems

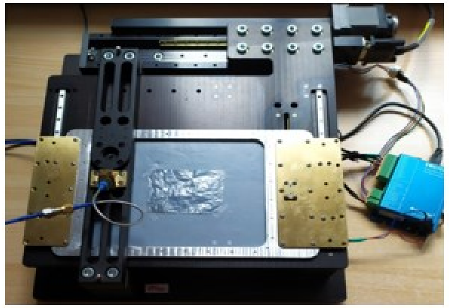
2D scanner designed with a modified 10 GHz SPDR

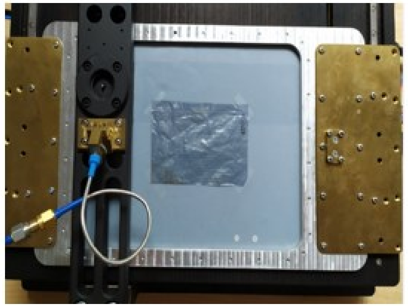
Finalist of the European Innovation Radar Prize 2021

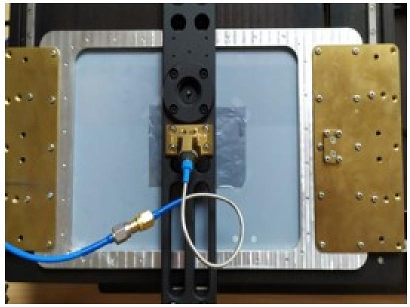
Scan of MW Susceptor after Heating

Example: unpopped & popped popcorn bag from ConAgra after Wikipedia

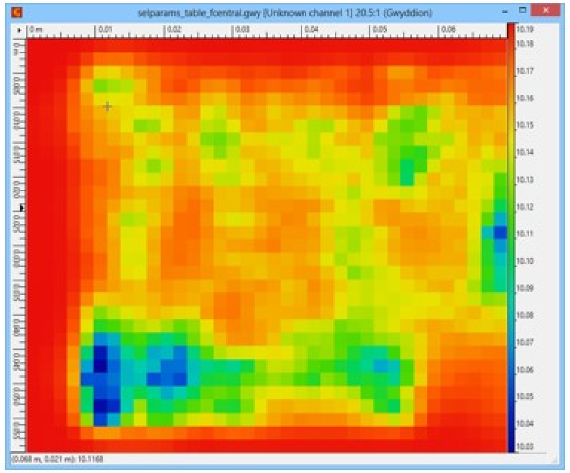
susceptor after 120sec of heating



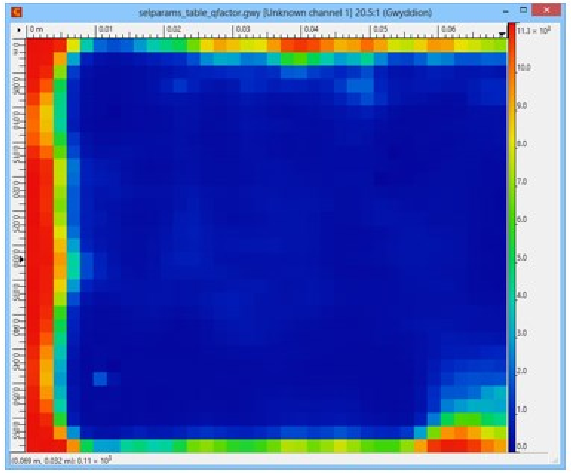




Size of sample: 50mm x 70mm
Scan area: 60mm x 70mm
Scan step: 2mm
Scan results: 1116 (31 x 36)
Measurement: 500 freq points
Total scan time: 9053sec (150 min.)
One step time: 8.11sec.



Scan results of central frequency

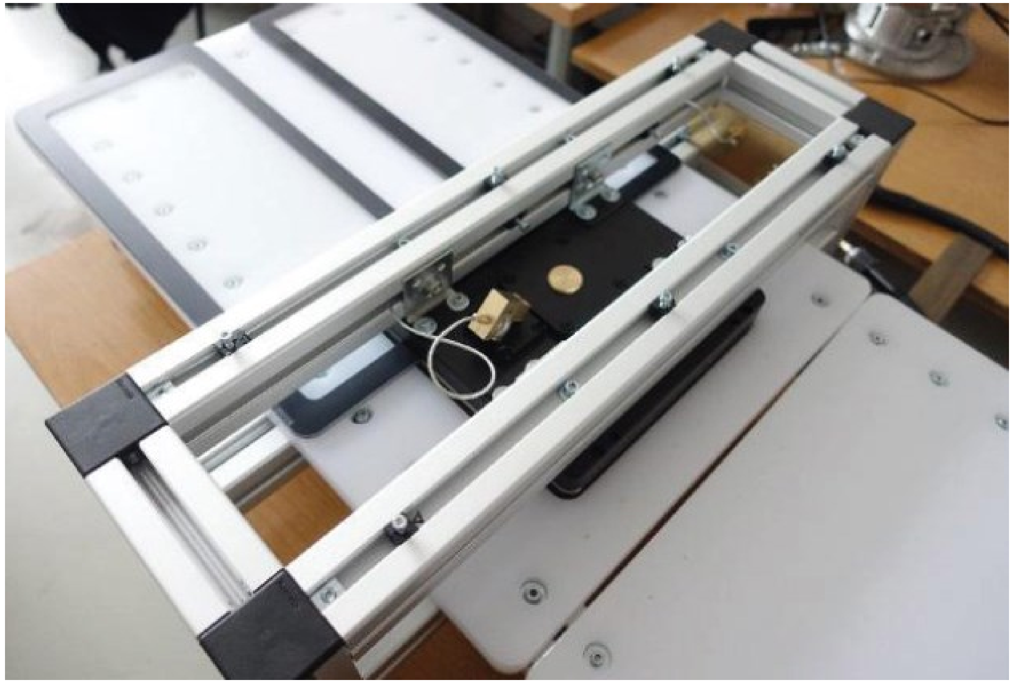


Scan results of Q-Factor

presented at:

17th International Conference
on Microwave and High Frequency Heating
9-12 September 2019, Valencia, Spain

Other 2D Imaging Instruments



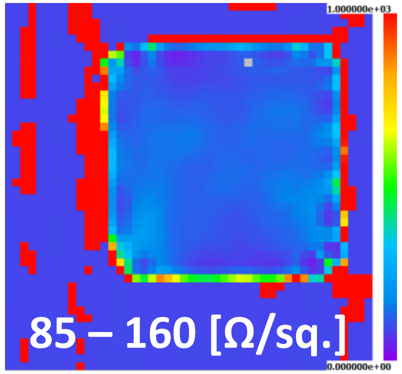
2 GHz SPDR manual scanner
for MW oven glass panes

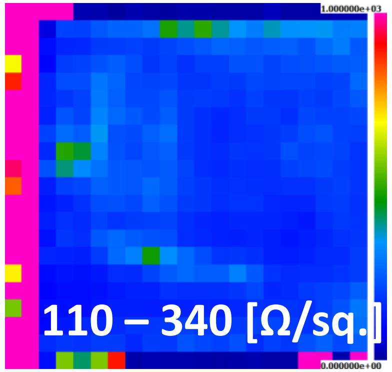
based on request by B/S/H/

10 GHz SiPDR automatic scanner
for conductive sheets

Nano Bat

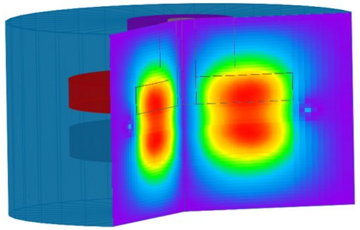
Surface resistance image of a battery anode
before & after cycling

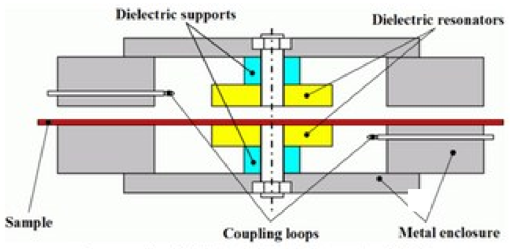




Basic Units for Material Measurement

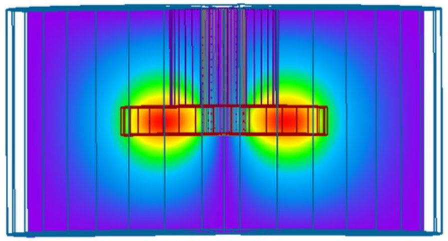
SPDR
Split-Post Dielectric Resonator

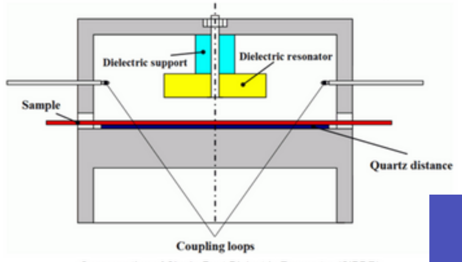




Cross section of Split Post Dielectric Resonator (SPDR)

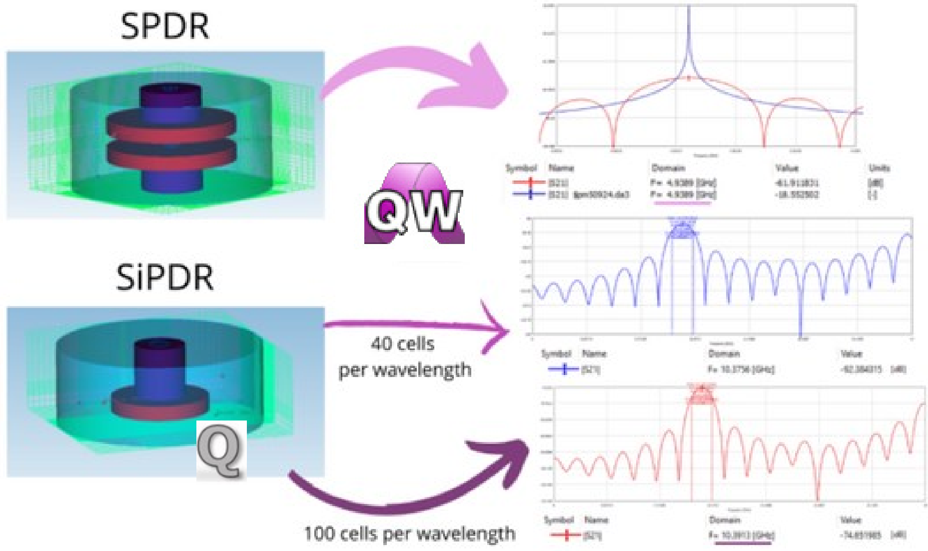
SiPDR
Single-Post Dielectric Resonator

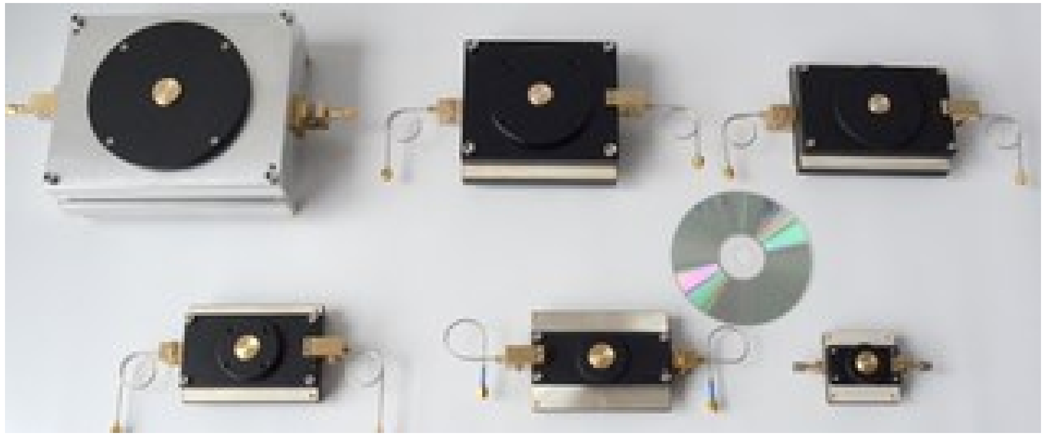


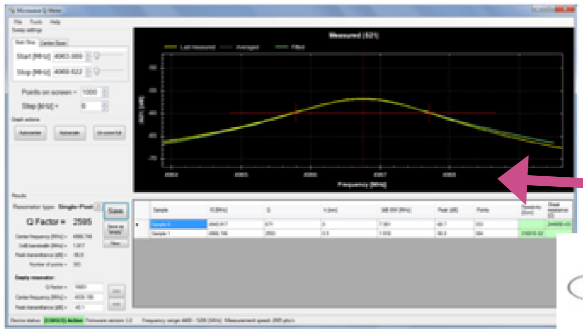


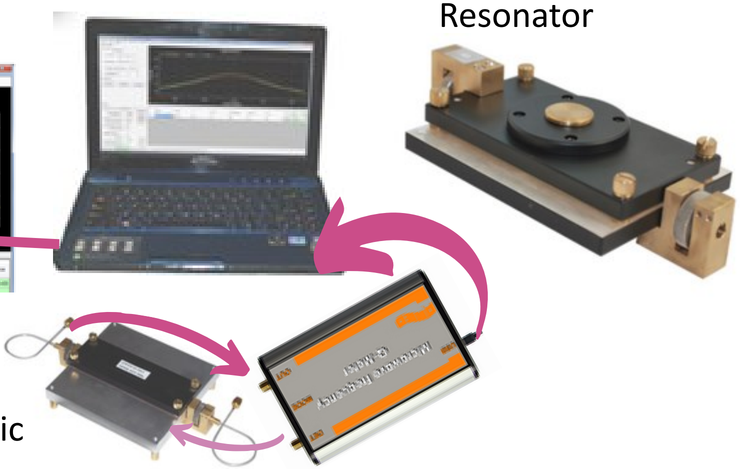
Cross section of Single Post Dielectric Resonator (SiPDR)

QuickWave Modeller







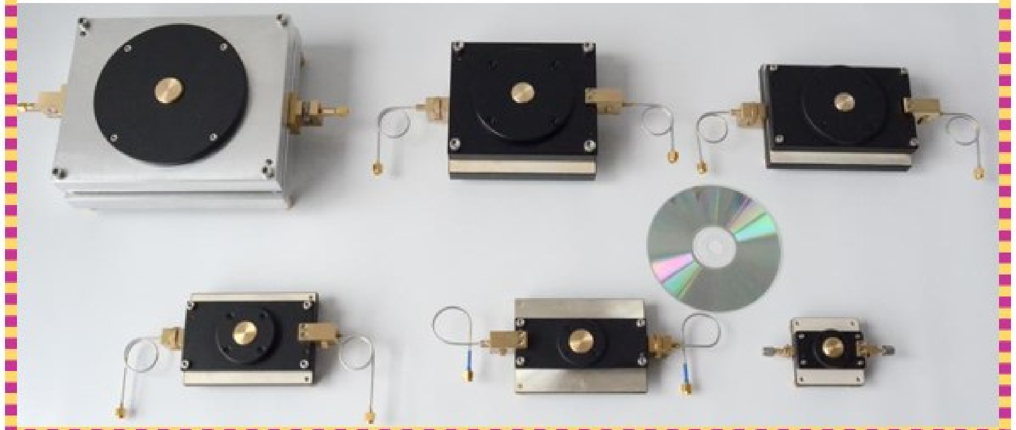


Split Post Dielectric Resonator

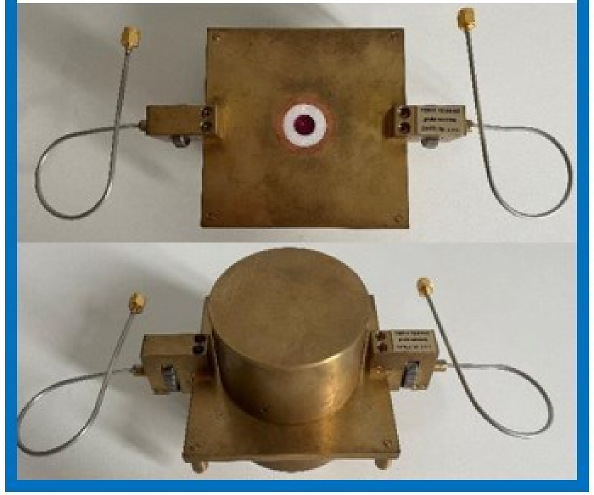
Single Post Dielectric Resonator

The Portfolio

Split-Post Dielectric Resonator, typical units for 1.1 GHz -15 GHz
for laminar low-loss dielectric materials



Sapphire Resonators (SaDR)
for metal foils
13.5 / 20 GHz



more recent
FPOR

Fabry-Perot Open Resonator
automatic span,
quasi-continuous
20 .. 120 GHz

5 GHz SiPDR
for resistive sheets

TE01δ cavities,
typically 1 GHz – 10 GHz
for bulk low-loss dielectrics

LAMINAR LOW-LOSS DIELECTRICS

METALLIC OR RESISTIVE SHEETS

APPLIED IN TEMPERATURE-VARYING CONDITIONS

QWED's Popular Dielectric Resonators

IMS
Connecting Minds. Exchanging Ideas.

Round-Robin Industrial Validation (1)

The Coolest Ideas Under the Sun
SAN DIEGO 2023

iNEMI
International Electronics Manufacturing Initiative

Our project: iNEMI

- 3M
- AGC-Nelco
- Ajinomoto USA
- AT&S
- Centro Ricerche FIAT-FCA
- Dell
- Dupont
- EMD Electronics (Co-Chair)
- Flex
- Georgia Tech
- Showa Denko Materials
- IBIDEN Co Ltd
- IBM
- Intel
- Isola
- ITRI (Co-Chair)
- Keysight (Co-Chair)
- MacDermid-Alpha
- Mosaic Microsystems
- NIST
- Nokia
- Panasonic
- QWED
- Shengyi Technology Company
- Sheldahl
- Unimicron Technology Corp
- Zestron

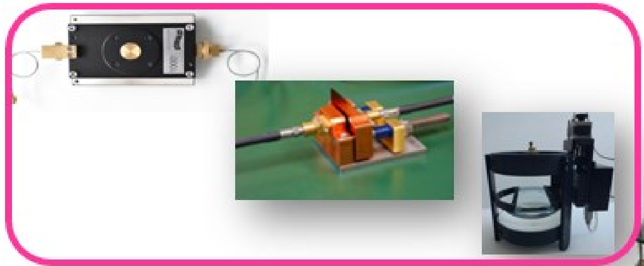
Sample Material Requirements
- Stable, Low loss
- Low moisture absorption / temperature dependency
- Isotropic
- Good mechanical & handling properties

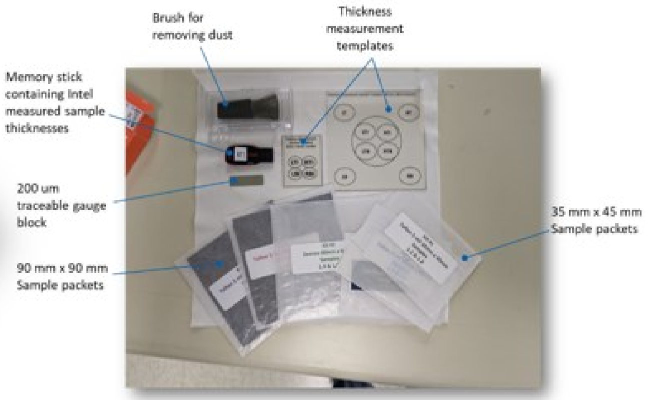
1st Project Stage
- Precision Teflon
- Cyclo Olefin Polymer

2nd Project Stage
- Rexolite
- Fused Silica

Industrial
- Automotive

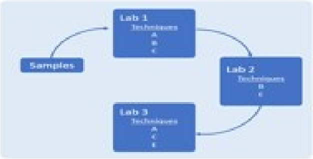
Techniques Included
- Split Post Dielectric Resonator
- Split Cavity Resonator
- Fabry-Perot
- Balanced Circular Disk Resonator





→ Frequency Span : 10GHz – 100GHz with overlaps

10 Laboratory Round Robin



10 Sample Kits Created
- Sample sizes 35 mm x 45 mm, 90 mm x 90 mm
- circulated between 10 labs

Note: the iNEMI banchmarking was aimed at 5G technologies, at higher than popular ISM frequencies,
but its reference was 10GHz SPDR, which is of the same family as QWED's SPDRs covering 915MHz, 2.45 GHz and 5.8GHz bands.

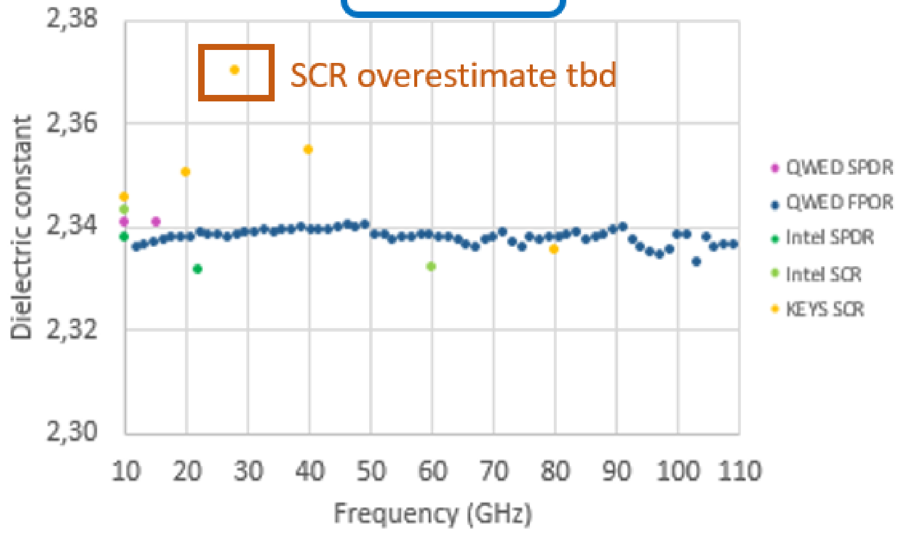
Round-Robin Industrial Validation (2)

A small but representative subset of the bencharking results, (out of tens of thousands of measurement points)

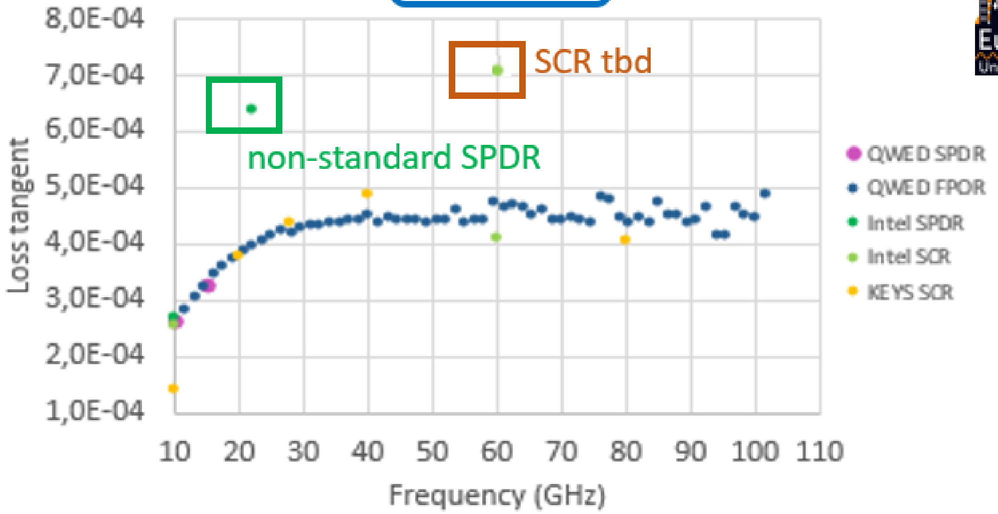
3 labs, 3 techniques, 14 laboratory setups

Intel - SCR at 10 / 60 GHz and SPDR at 10/ 20 GHz,
Keysight - SCR at 10 / 20 / 28 / 40 / 80 GHz
QWED - SPDR at 10/ 15 GHz and FPOR over 10-110GHz.

dot colours denote testing sites



Dk spread < 1% (within ± 0.5% from average)
(< 2% incl. outliers)



> 40GHz 2x increase in Df compared to 10GHz

presented at:

EXCEL, LONDON 2-7 APRIL 2022
EuMW 2021 United in Microwaves
www.eumw2021.com

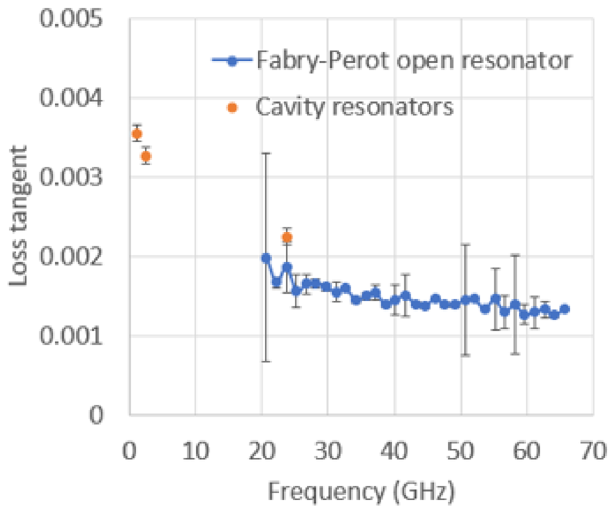
All data sets are available to iNEMI members
www.inemi.org

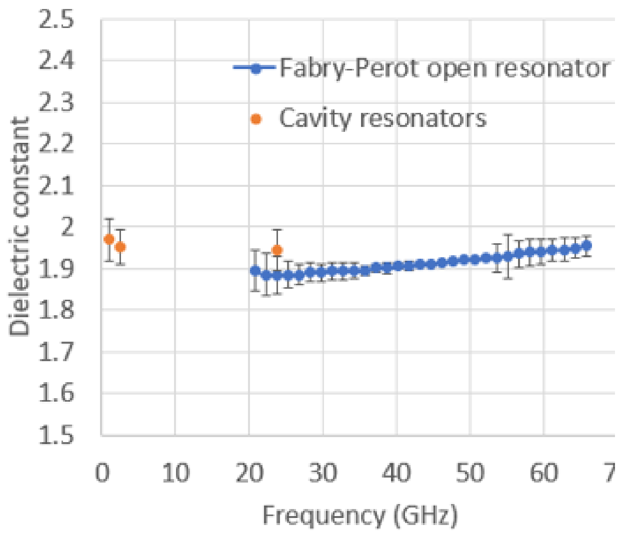
Note: the iNEMI banchmarking was aimed at 5G technologies, at higher than popular ISM frequencies, but its reference was 10GHz SPDR, which is of the same family as QWED's SPDRs covering 915MHz, 2.45 GHz and 5.8GHz bands.

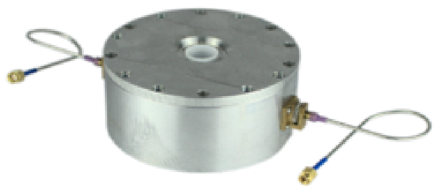
Measurements of Liquids & Powders

- Customised to low or high loss materials
- Characterisation with resonant methods
  - Cavity devices
  - Fabry-Perot Open Resonator (prototype)
- Cavity fixtures available within 1 – 30 GHz
- Cavity measurements at varying temperature
- FPOR targeted frequency range: 20 – 67 GHz

Popular coolant liquid







example cavities @1GHz & 24 GHz

FPOR

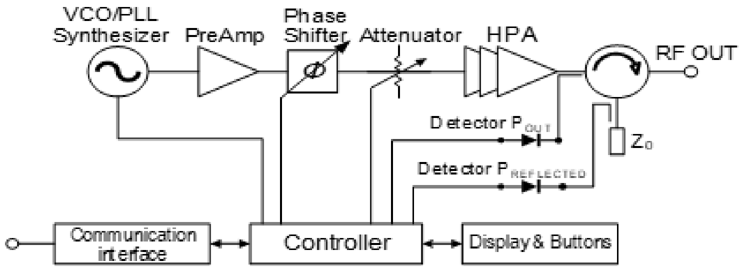
For more details, come to MicroAPPS:

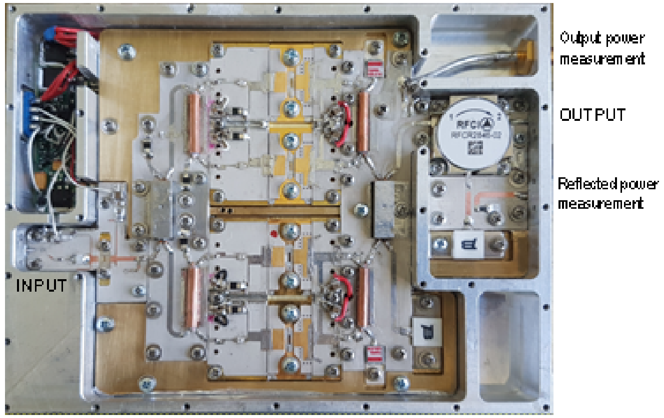
TUMA21
Tuesday, 14:30-14:45
MicroApps Theater, Booth 2447

or QWED Booth 2537 any time!

A Complete Design Cycle: Example 1

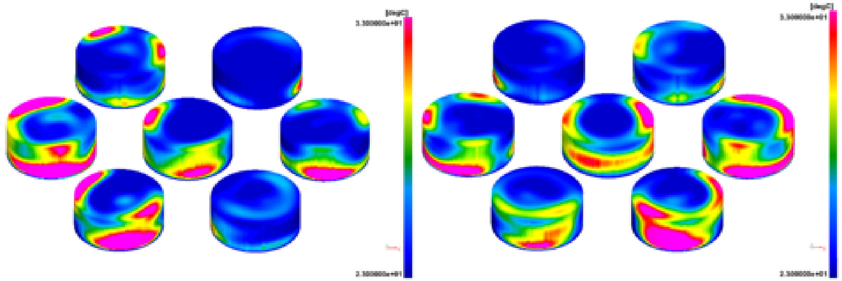
Solid-State Computer-Controlled Experimental Domestic Microwave Oven



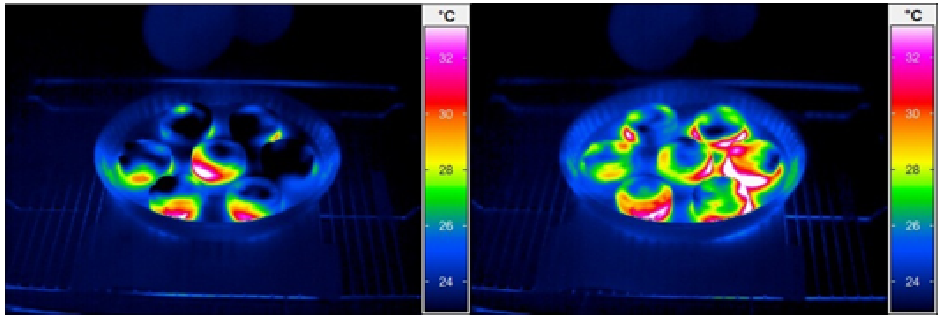


Multifunctional heating source
based on two-stage double-balanced GaN HEMT HPA
(Prof. W.Wojtasiak, Dr. D.Gryglewski Warsaw Univ.Tech.)

Temperature in mashed potato cookies, after 60 s of heating ,
for different relative phase shifts (added 110 degrees) between two sources.
(*Development of packaging and products for use in microwave ovens*, Elsevier, 2020)



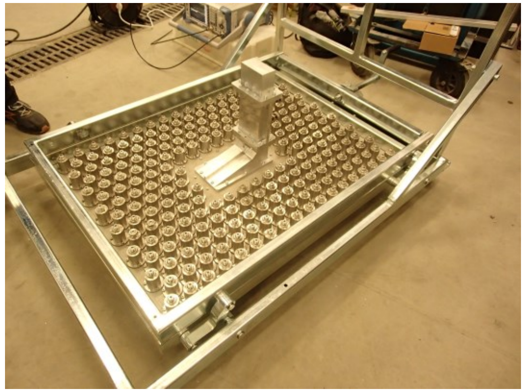
QuickWave modelling by QWED



Photos courtesy BSH HAUSGERATE GmbH, Traunreut, Germany.

B/S/H/

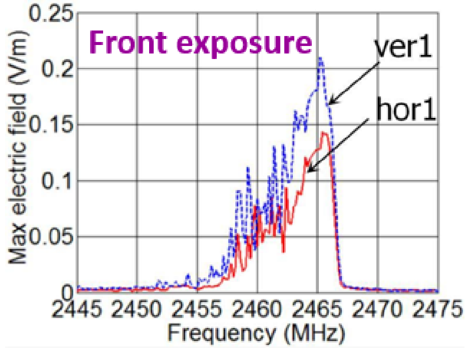
A Complete Design Cycle: Example 2

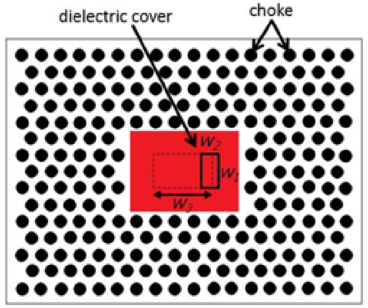


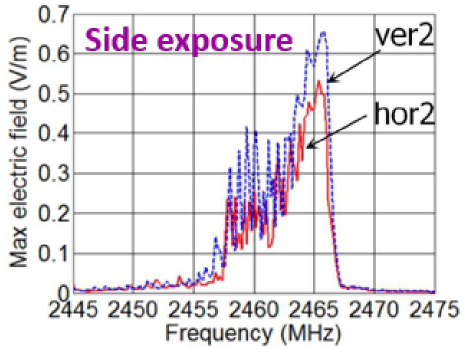
2.45GHz Aplicator for Road Repair (with Chokes & Full Safety System)

PBS Program Badań Stosowanych
Narodowe Centrum Badań i Rozwoju
Instytut Badawczy Dróg i Mostów

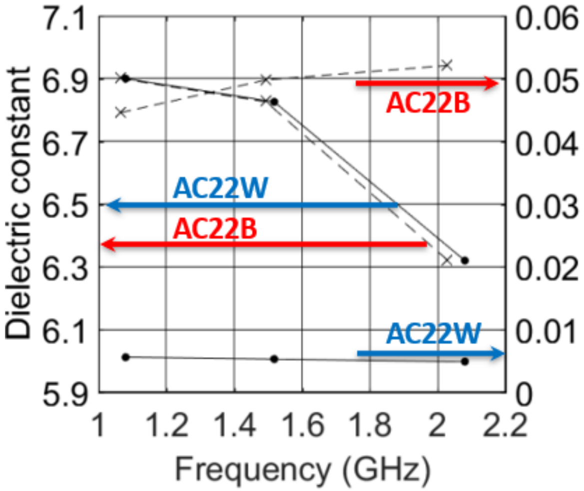
- Magnetron bandwidth: 10 MHz
- Front exposure ca. 9x smaller than side exposure
- EC recommendation: 10 W/m^2 (61 V/m)
- Power can be safely increased up to 30 kW and beyond

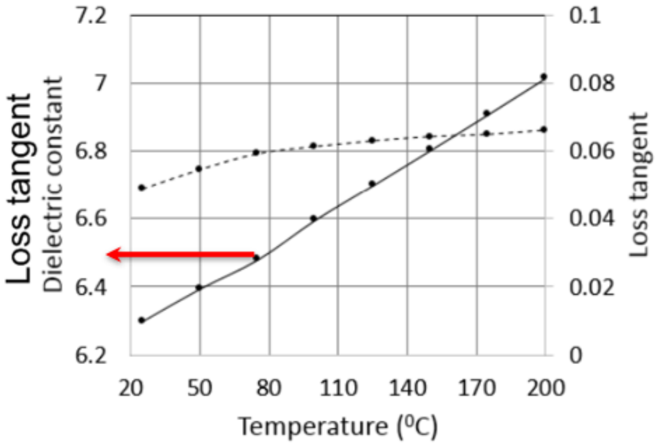






Measurements undertaken with cavity resonators.





AC22B – asphalt with basalt aggregates
AC22W – asphalt with limestone aggregates

Asphalt binder: ε_r = 2.65, tanδ = 0.00163 @ 2.45GHz

Basalt aggregates: ε_r = 4.05, tanδ = 0.165 @ 2.45GHz

presented at: International Microwave Power Institute

IMPI 56 Symposium
June 14 - 17, 2022
Savannah, Georgia, USA

Conclusions

- Computer Aided Design of microwave power systems requires creating a **Digital Twin** of the physical system. This is based on:
  - Physics Equations (and efficient solvers)
  - Material Relations (often with data coming from in-house measurements)
- Our **contributions to both above fields** have been presented, including:
  - modelling of multiphysics processes (radiation, fluid flow) with bilateral coupling
  - faster solvers (exploring structure symmetries – BoR or modern hardware)
  - new instruments for materials' characterisation: surface imaging, liquids, powders
- Our tools have been **applied to real-life problems** provided by our industrial and project partners, which we kindly acknowledge.

Acknowledgement

The relevant work of QWED team is currently co-funded by:

The National Centre for Research and Development

the *Polish National Centre for Research and Development* under contracts *M-ERA.NET2/2020/1/2021* and *M-ERA.NET3/2021/83/I4BAGS/2022*.

M-ERA.NET

M-ERA.NET 3 has received funding from the *European Union's Horizon 2020* research and innovation programme under grant agreements *No 958174*.

ULTCC6G_EPac

I4Bags

We kindly acknowledge the collaborations with our partners in the above European projects.

iNEMI International Electronics Manufacturing Initiative

We acknowledge the iNEMI "5G" partnerships for round-robin experiments and discussions.

Special thanks to all our industrial clients and partners for driving our developments and their kind permission to publish selected industrially-representative results.

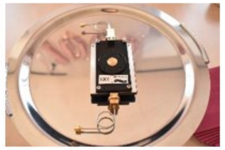
Thank you for your attention!

1997: QWED founded
1998: Prime Minister Award

Prof. Jerzy Buzek awarding QWED team in 1998
Prime Minister of Poland 1997-2002
President of the European Parliament 2009-2012

2022: our 25 years

2020: sale of our 1000th resonator



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meet QWED team in Booth #2537

Connecting Minds. Exchanging Ideas.

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