NFMO 2019

Modelling - based methodology for downscaling dielectric resonator material measurements of material surfaces

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→ How we apply general-purpose EM software to enhanced material measurements & processing

with contributions from: M.Olszewska-Placha, M.Sypniewski, J.Rudnicki

QWED MMAMA IEEE MTT-S

Acknowledgements

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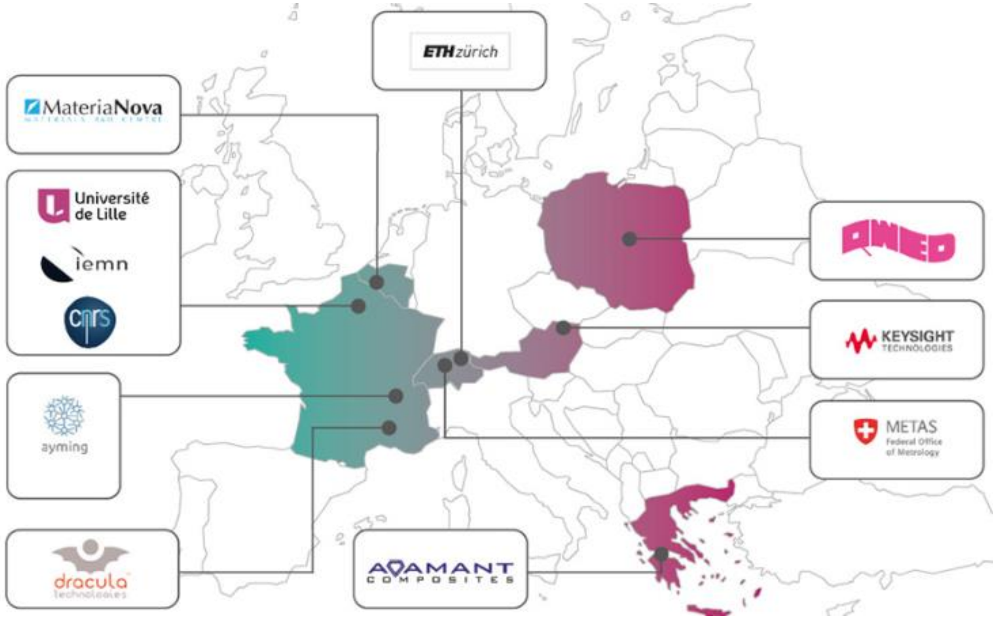
(website: www.mmama.eu)



THE EUROPEAN INFORMATION TECHNOLOGY PRIZE *Winner*

Simulations were conducted with QuickWave EM software, developed & commercialised 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 a basis for precise material measurements
- Split-post dielectric resonator (SPDR): why it has become a standard
- Other types of dielectric resonators
- SPDR measurements of larger surfaces
- Resolution enhancement of material images
- "Transfer of technology" from other application & the applications themselves:
    - "*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
- Modelling of SMM tips for material measurements at nano-scale
    - unconventional (but constructive) definitions of inmpedance and S-matrix
- Conclusions

Dielectric resonator methods for material measurements

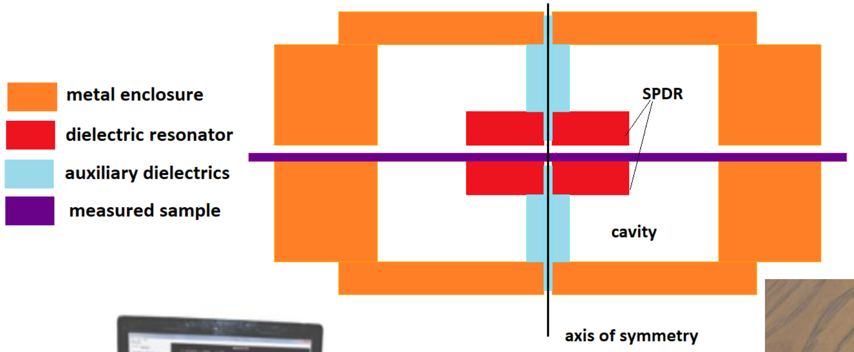
SUT of $\varepsilon_s = \varepsilon_s' - j\,\varepsilon_s''$ is inserted into DR:
resonant frequency changes from f_e to f_s
Q-factor changes from Q_e to Q_s.

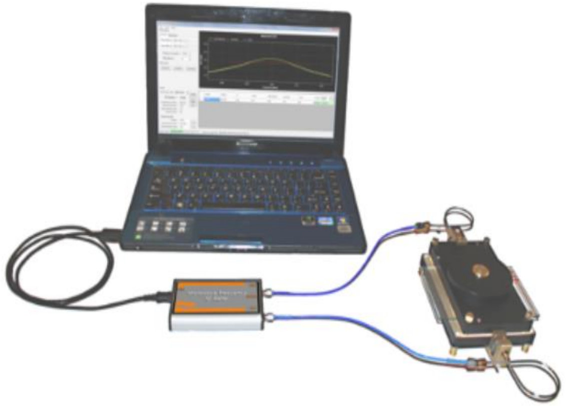
$$\frac{f_e - f_s}{f_e} \approx \frac{h}{2C} \iint_S \left[\varepsilon_s'(x,y) - 1\right] \left|E(x,y)\right|^2 dS$$

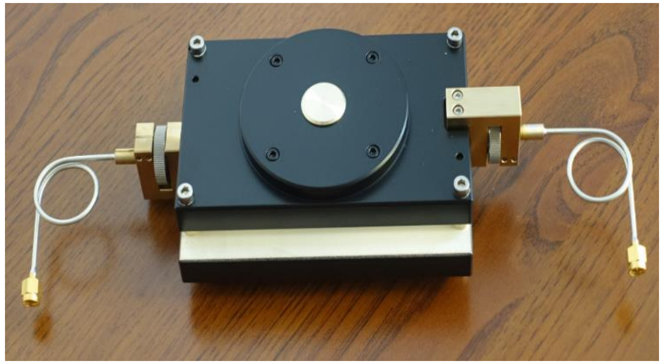
$$\frac{1}{Q_s} - \frac{1}{Q_e} \approx \frac{h}{C} \iint_S \varepsilon_s''(x,y) E^2(x,y)\, dS$$

$$C = \iiint_V \left|E(x,y)\right|^2 dV$$

Most popular example: Split-Post Dielectric Resonator





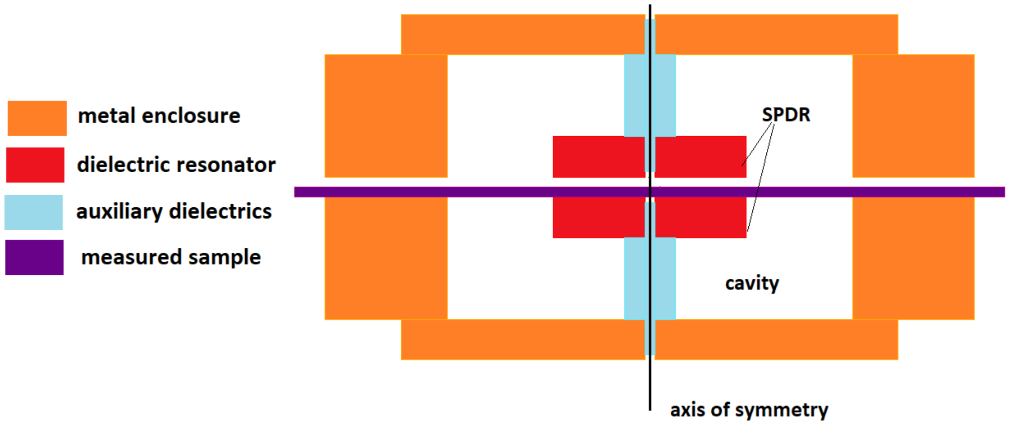


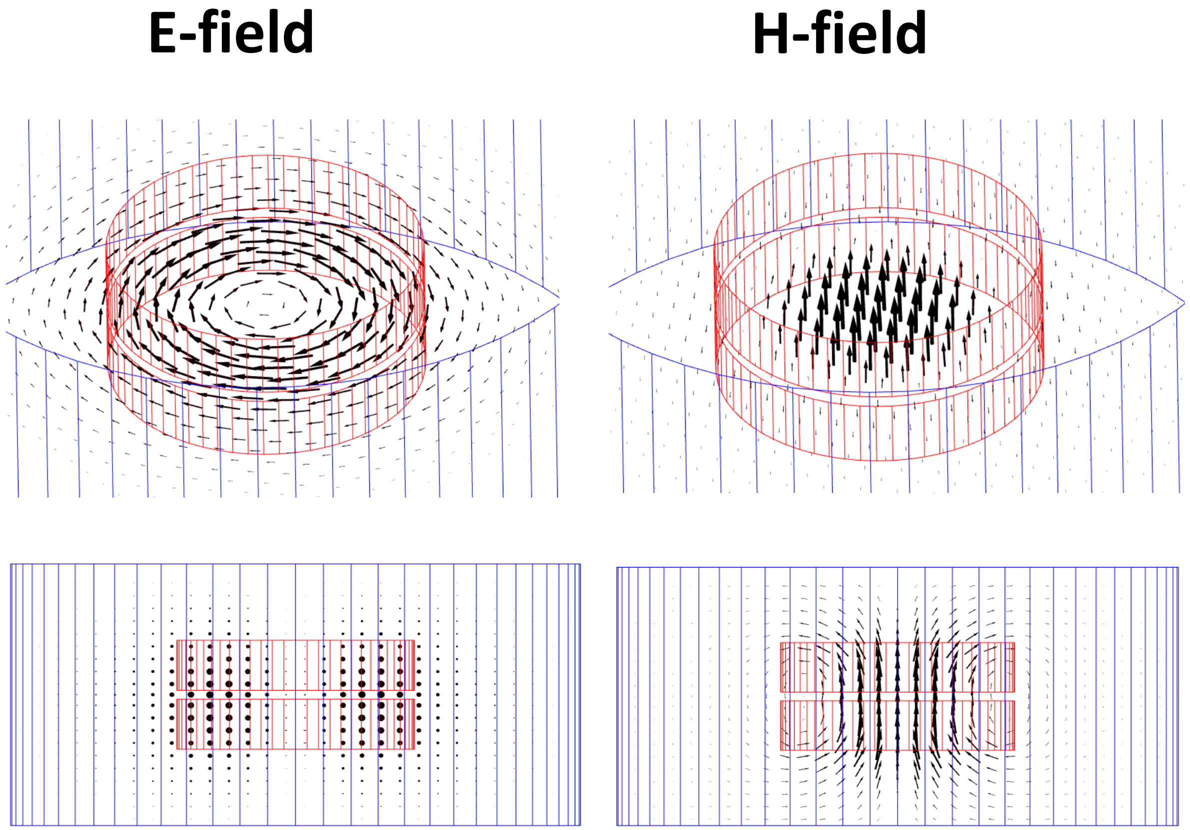
field assumed invariant in *z*-direction
S is called the DR's *head*
sign ≈ reflects field patern changes caused by SUT

minimise

field variation in *z* (or take it into account)
field changes due to SUT

Fields in SPDR

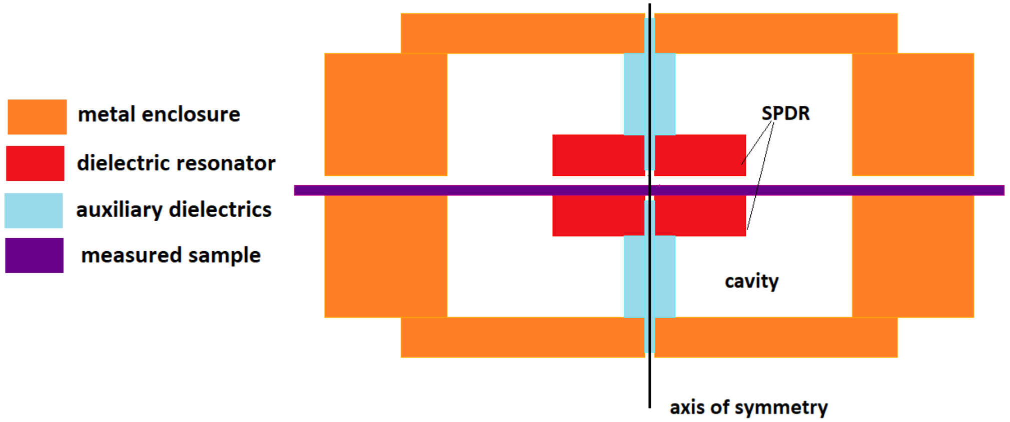


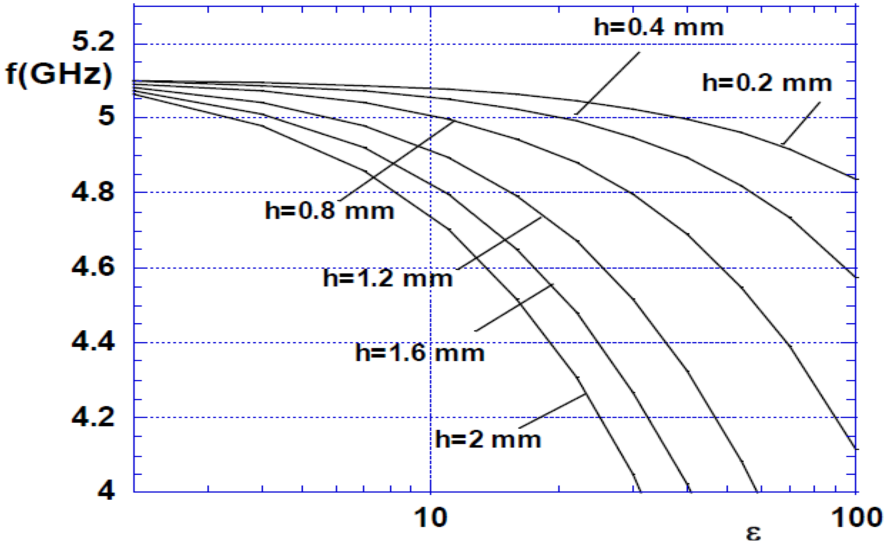


- resonant mode with EM fields mostly confined in and between those ceramic posts → minimial losses in metal enclosure
- H-field is only vertical at the side wall of the enclosure → only circumferential currents in side wall → no radiation through slot
- E-field tangential to SUT → air slots between SUT and posts have negligible effect
- **easy SUT insertion through slot, no dismatling, NDT method**
- all EM energy injected through the coupling loops in contained within in the SPDR "head" (inside the enclosure)
- an estimated 95% of energy confined in and between the ceramic posts
- **calibration only once, at manufacturing**

Accuracy of SPDR measurements

QWED SPDRs for: 1.1, 1.9, 2.5, 5, 10, 15 GHz





accuracy for *ε* typically 0.3%

measurable losses tanδ ~6 10^{-5}

$$\Delta\varepsilon/\varepsilon = \pm(0.0015 + \Delta h/h)$$

$\Delta\tan\delta = \pm 2 \cdot 10^{-5}$ or $\pm 0.03 \cdot \tan\delta$ whichever is higher

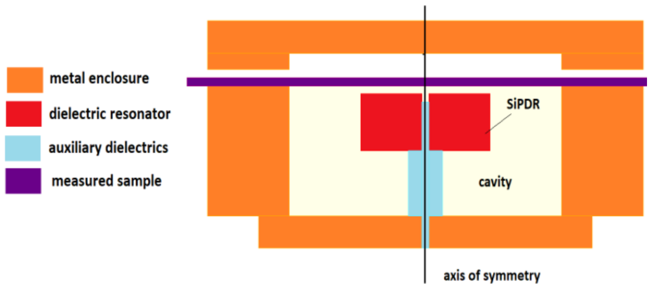
→ European Standard: IEC 61189-2-721:2015

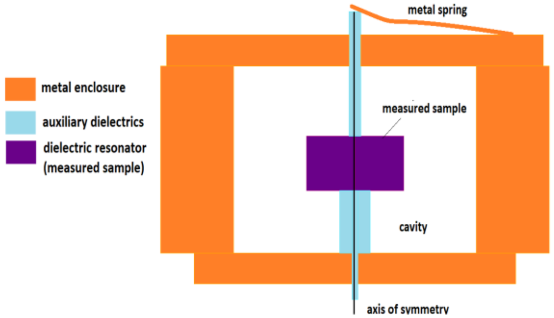
Limitations:

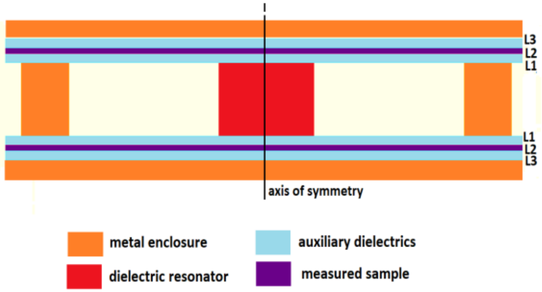
- **SUT thickness - slot size 0.6..6 mm**
- **SUT lateral min size ("absolute" EM constraint) - 14..120 mm**
- **spatial resolution 14..120 mm**
- **SUT lateral max size (mechanical construction) – 40..150 mm**

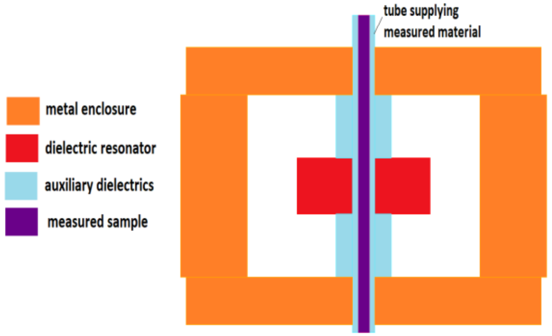
	Conductivity [1/(Ωm)]	Resistivity [Ω cm]	Surface resistivity [Ω/sq]
Range od SPDR applications	from 10^{-2} to 1	from 10^2 to 10^4	from 5 10^3 to 10^6
Range of SiPDR applications	from 1 to 10^7	from 10^{-5} to 10^2	from 2 10^{-4} to 5 10^3
Sapphire	> 5 10^6		

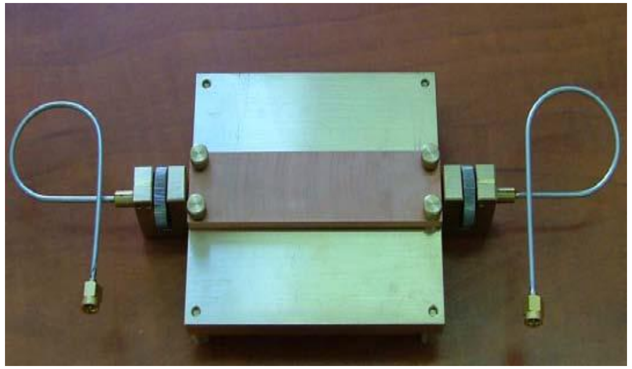
Other types of dielectric resonators (TE01δ)

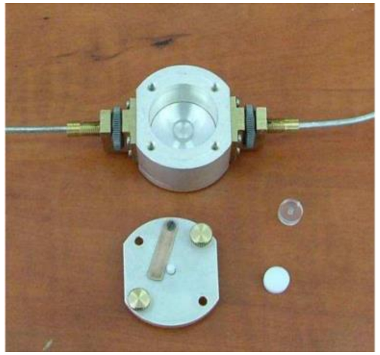


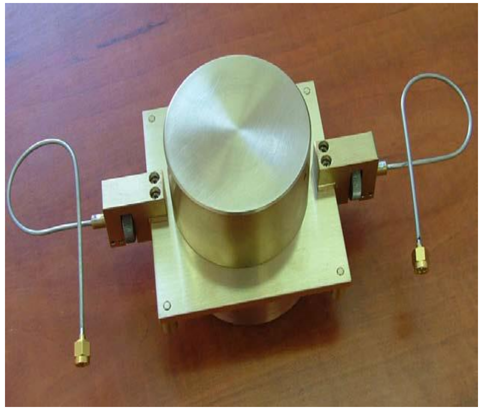


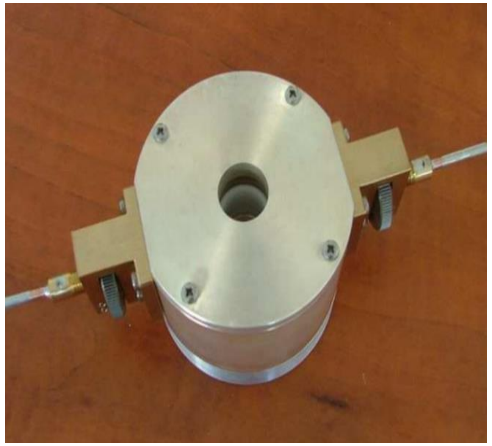












single-post
resistive sheets

cavity
resonating SUT
ultra-low-loss SUTs

sapphire
metal SUTs

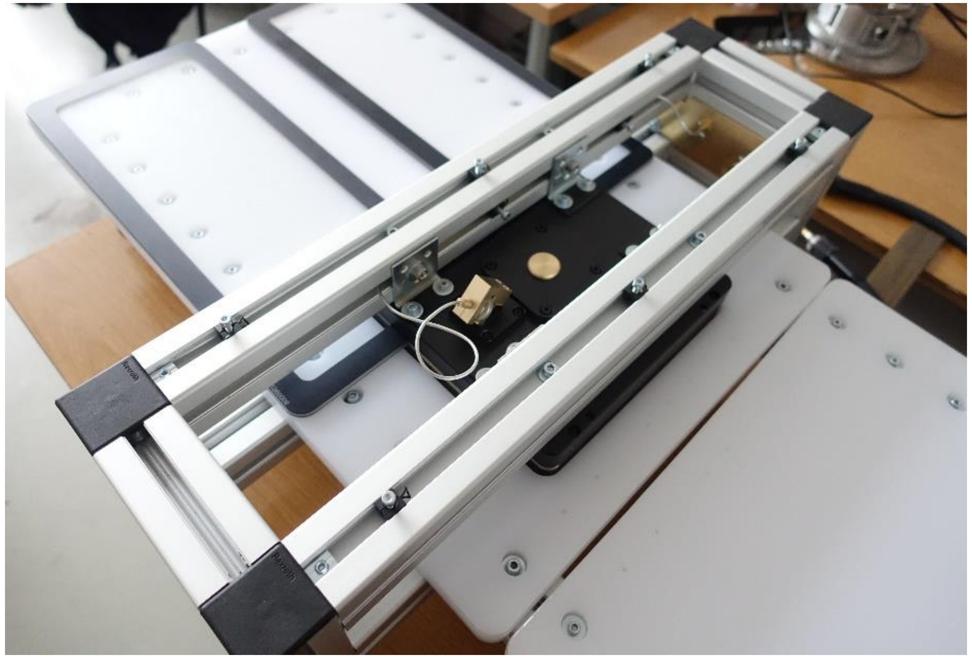
liquids & powders
can also heat

Surface scanning with SPDR

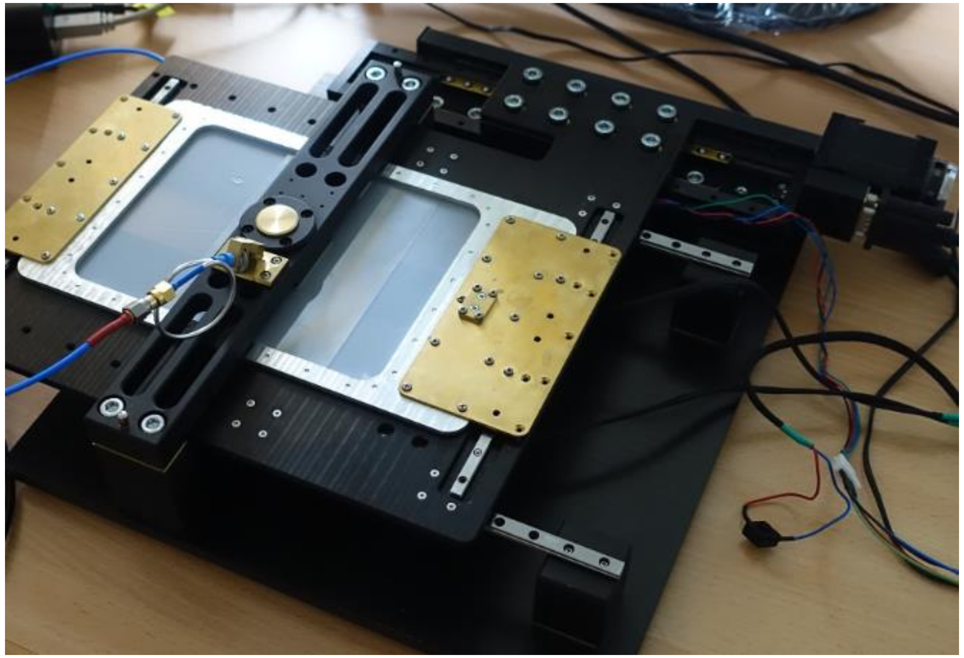
Obviating 1st out of 3 limitations:

- *SUT thickness - slot size 0.6..6 mm*
- **SUT lateral min size ("absolute" EM constraint) - 14..120 mm**
- **spatial resolution 14..120 mm**
- **SUT lateral max size (mechanical construction) – 40..150 mm**

manual scanner for large panes of glass (MW oven window)



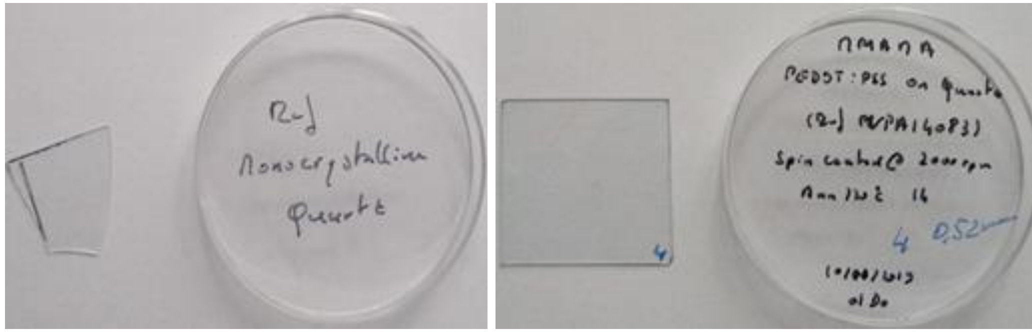
automatic scanner semiconductor wafers, composites, organic samples



Automatic surface scanning with SPDR

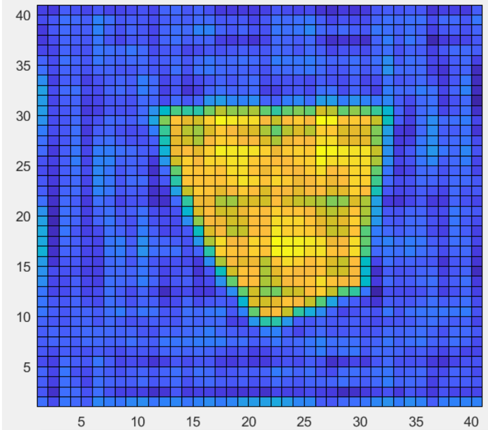
working with QWED Q-Meter

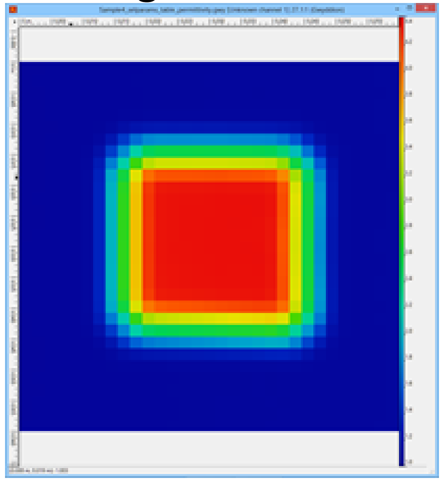
working with FieldFox
(Keysight hand-held VNA)

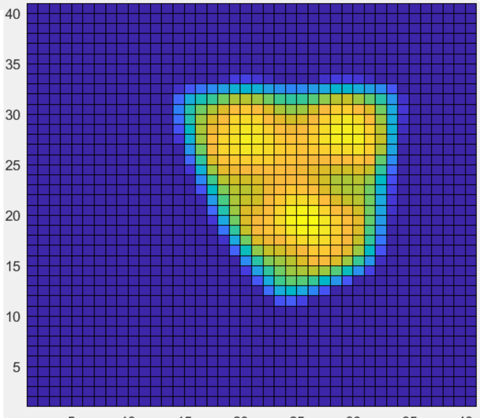


samples from MateriaNova

quartz substrate & deposited organic material



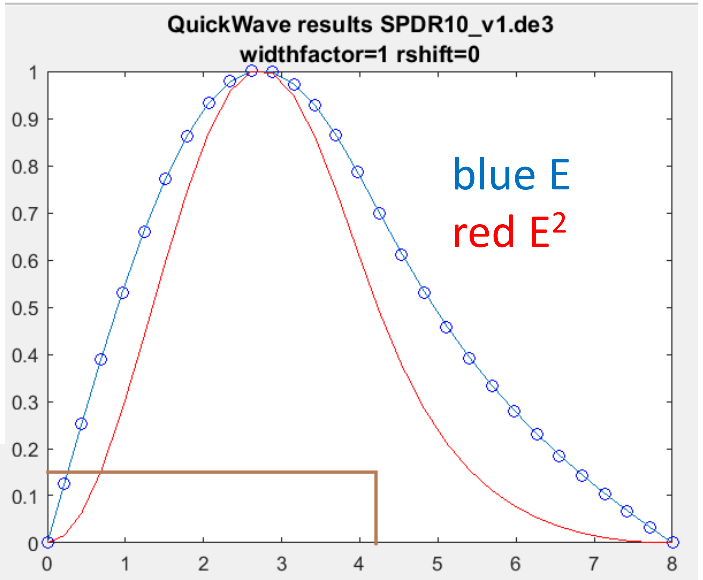




scanning step 1mm
but resolution ~16mm !

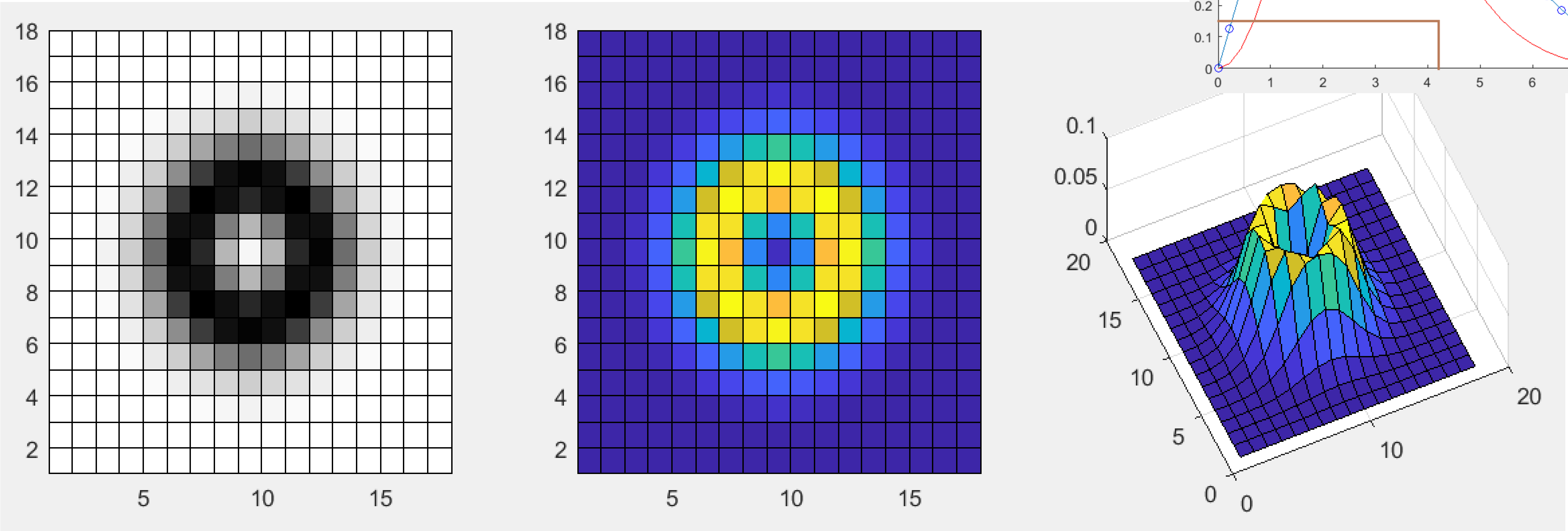
→ seek modelling-based resolution enhancement

Resolution enhancement for SPDR imaging



→ **Parameters are "averaged" within DR head**
but we know the field pattern

E-field in our 10 GHz SPDR as simulated in QuickWave:



Resolution enhancement for SPDR imaging

Consider the head meshed into (2K +1) x (2L+1) cells whose center with $E_T(0,0)$ is placed at cell (m,n) the scan.
For clarity, assume that the mesh is equidistant of raster a (a = 1mm in Fig. 1).
The measured energy change due to the SUT is:

$$\Delta W_{mn} = \frac{a^2 h}{2} \sum_{k=-K}^{K} \sum_{l=-L}^{L} \left[\varepsilon_s^{'}(m+k, n+l) - 1 \right] E_T^2(k,l)$$

Arranging the 2D array of ΔW_{mn} into a 1D vector W of elements ΔW_i, $i=(n-1)*M+m$, $i=1,..,M*N$,
and similarly the 2D array of permittivities $p_{s,mn}=(\varepsilon_s'-1)_{mn}$ into vector P:

$$[W] = [T]\ [P]$$

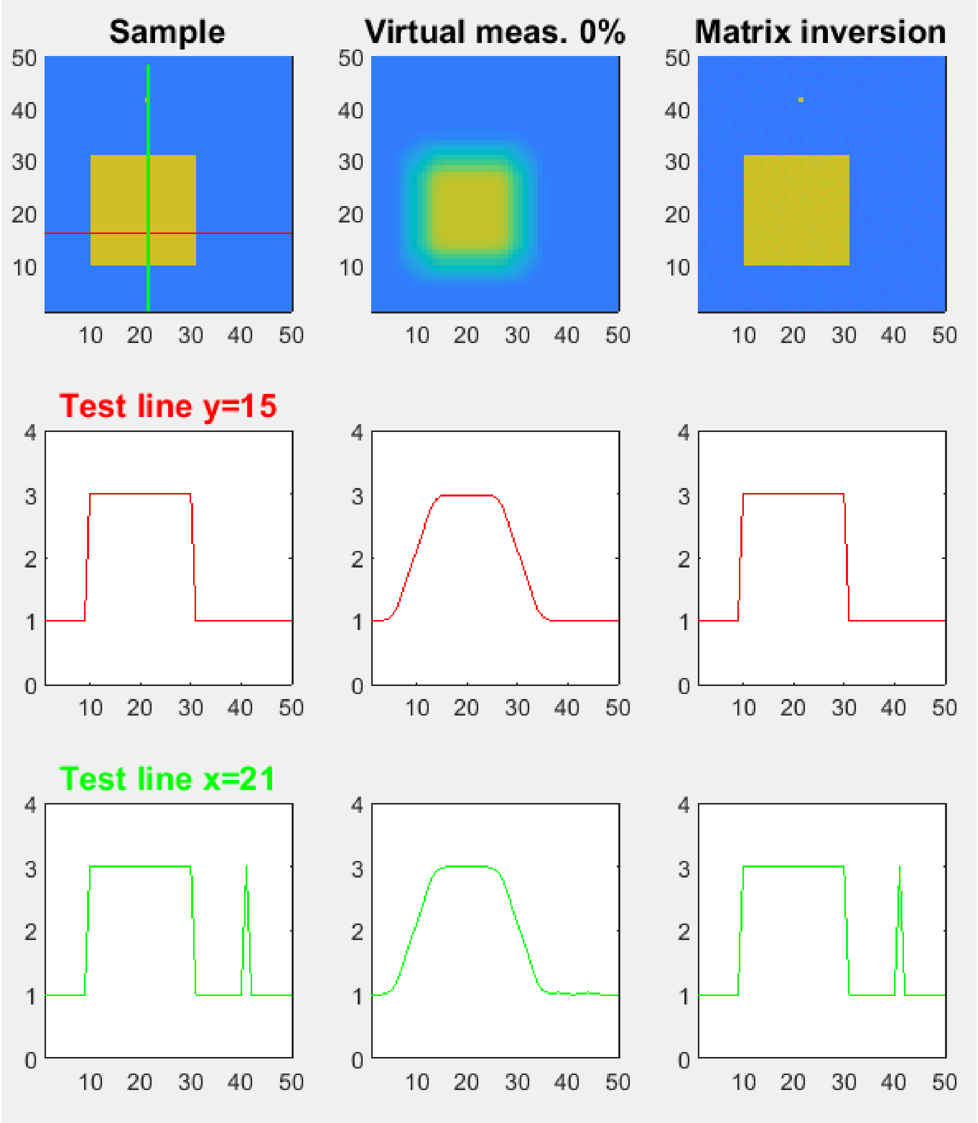
Matrix T is generated in such a way that element t_{rs} in row r and column s is equal to :
- $|E_T(k, l)|^2$ for $s= r+k+M\ l$ for $k=-K..+K$ and $l=-L...+L$)
- 0 for s not obeying the above condition.

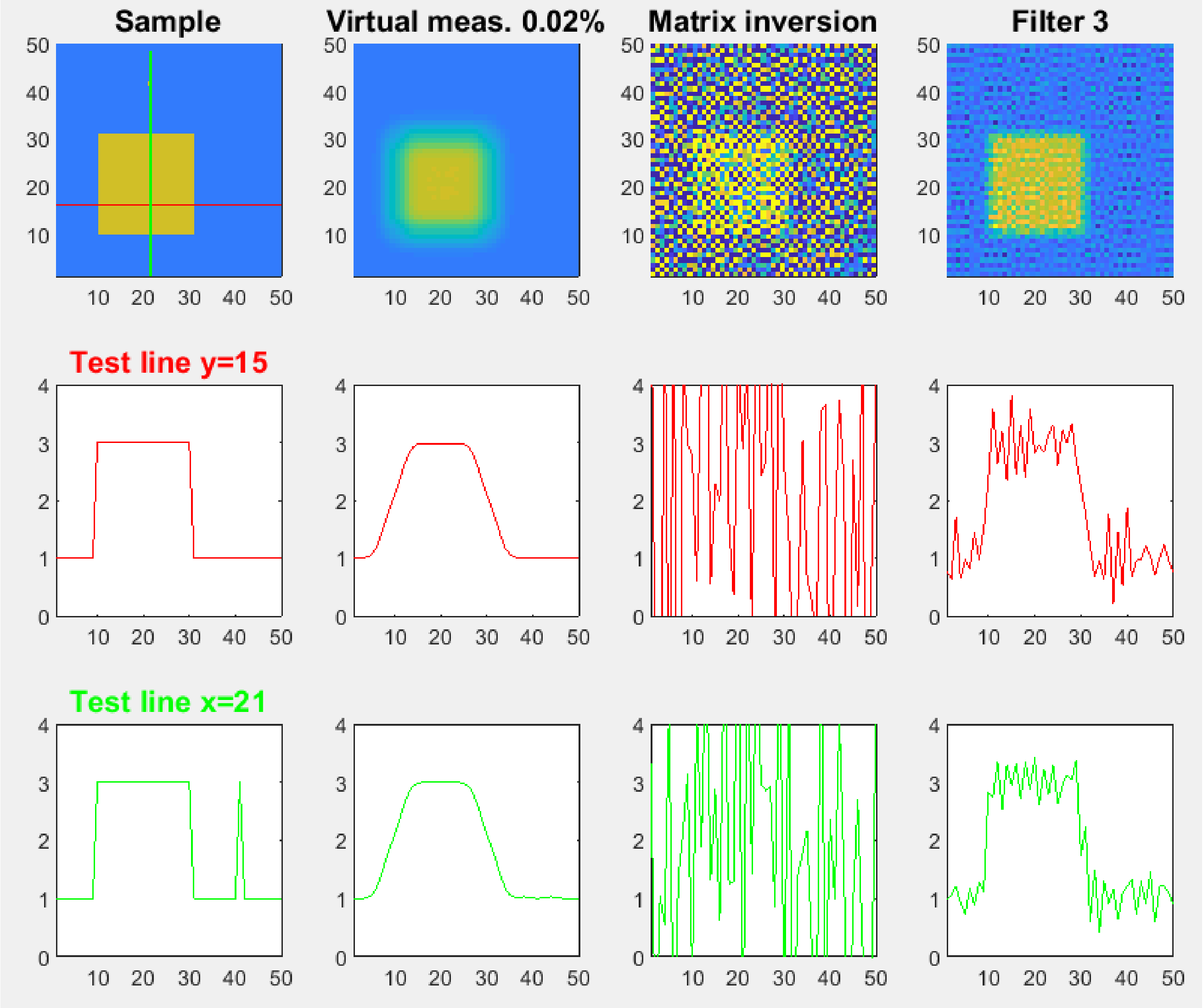
$$[P] = [T]^{-1}\ [W]$$

Space-domain,
***not* Fourier - domain**

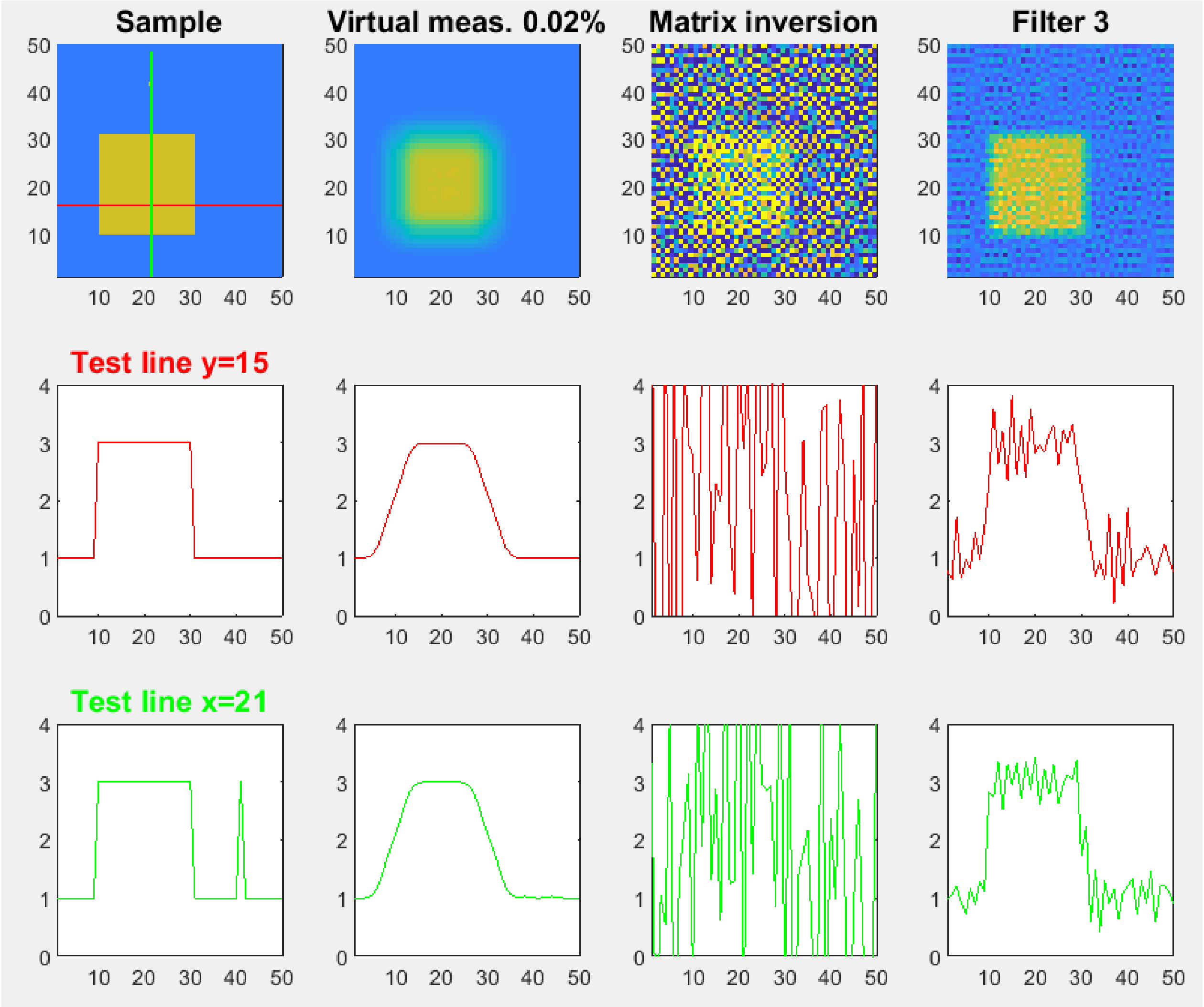
Matrix T is large, $M*N$ x $M*N$, but sparse and has a banded structure.

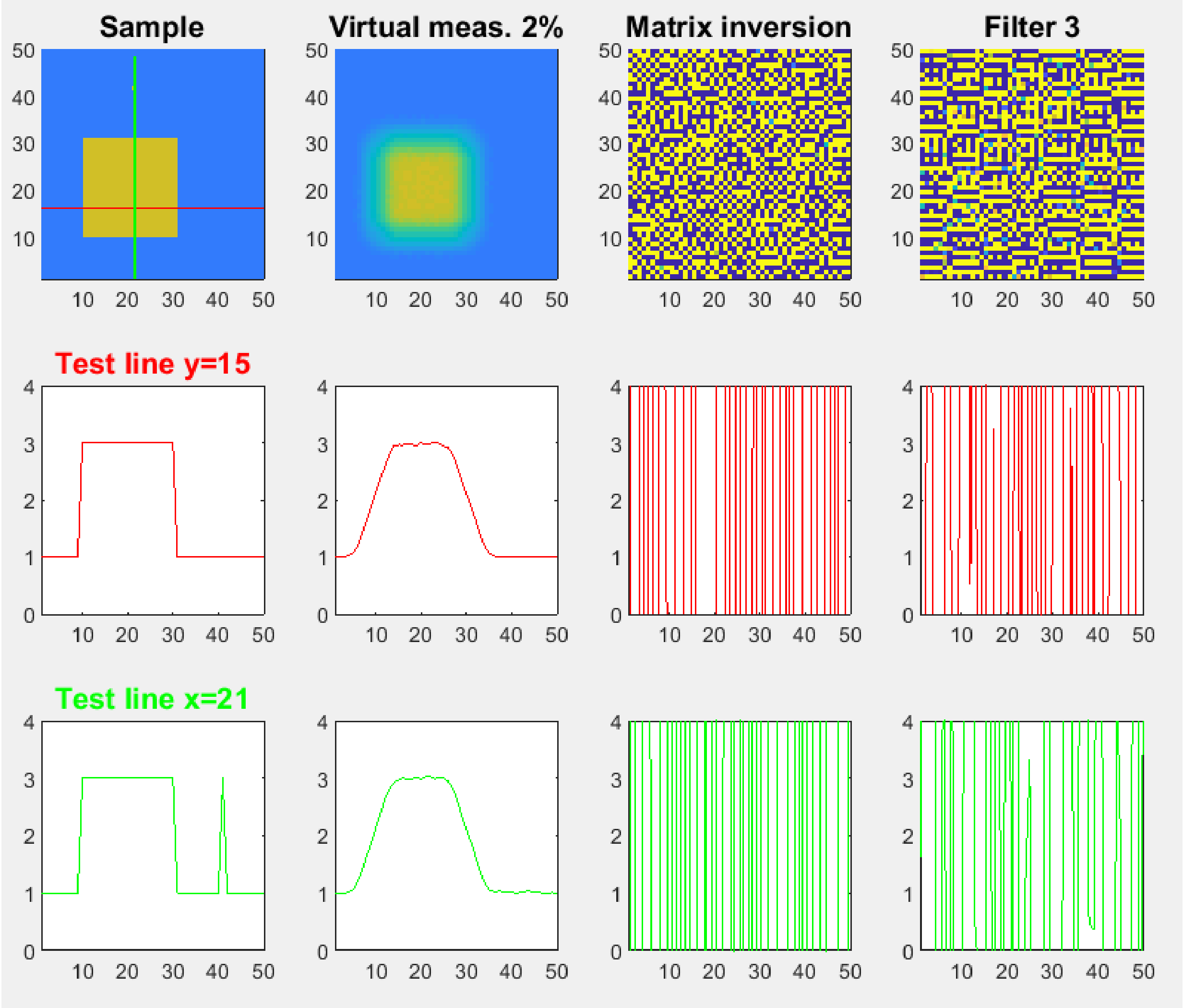
MATLAB experiments with virtual scans: matrix inversion of exact data & with noise



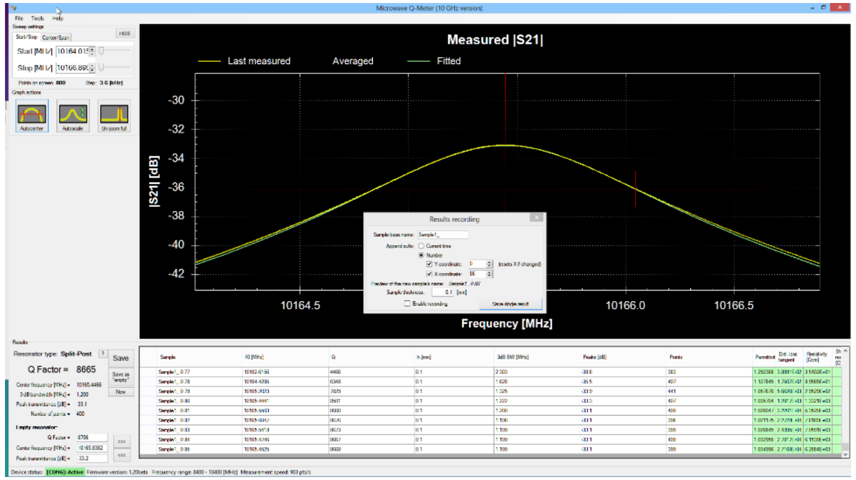


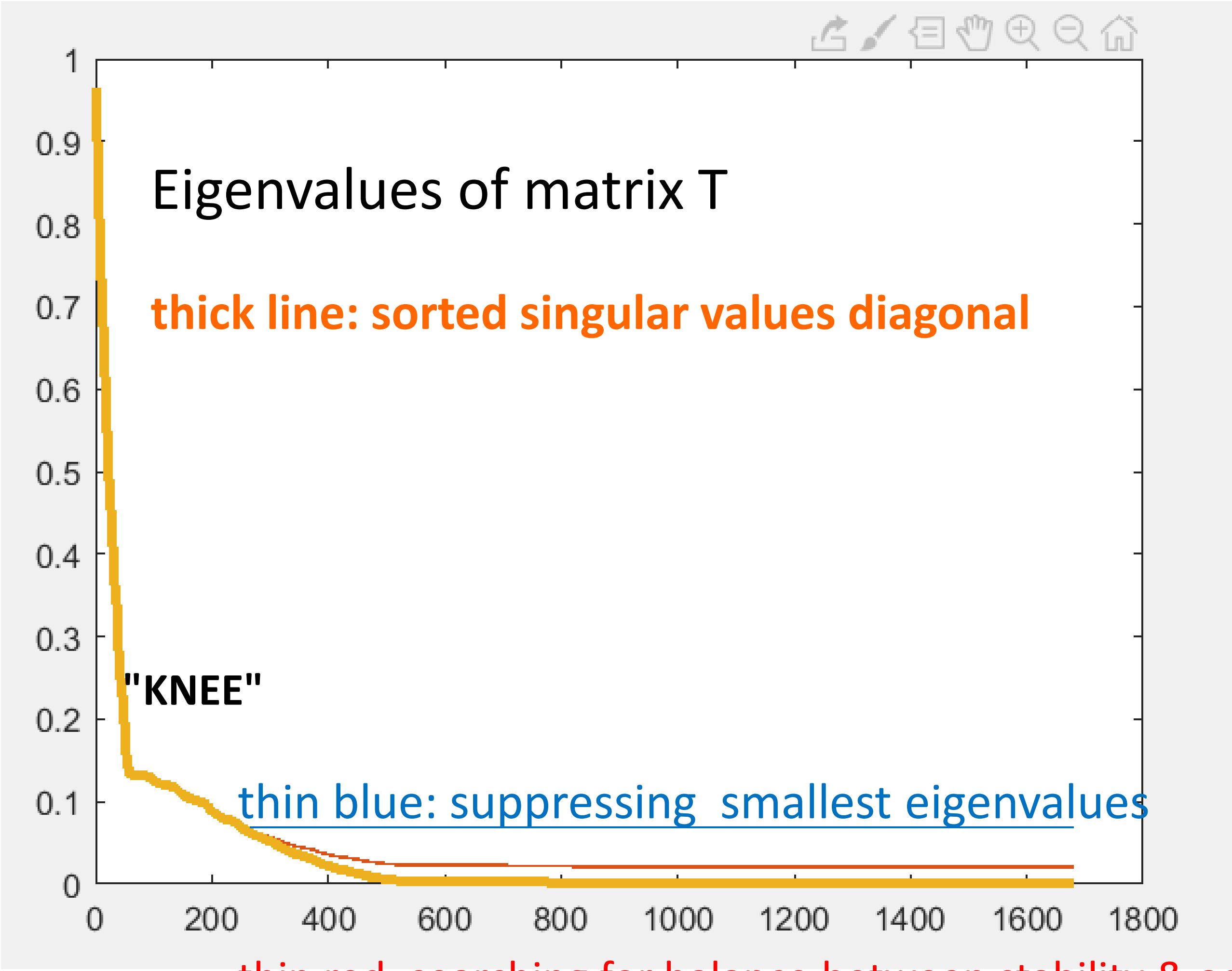
MATLAB experiments with virtual scans: matrix inversion with increased noised





Singular Value Decomposition





thin red: searching for balance between stability & accuracy

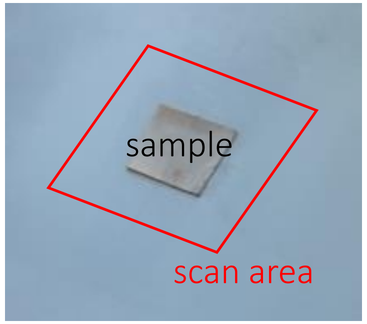
scan area 41x41mm

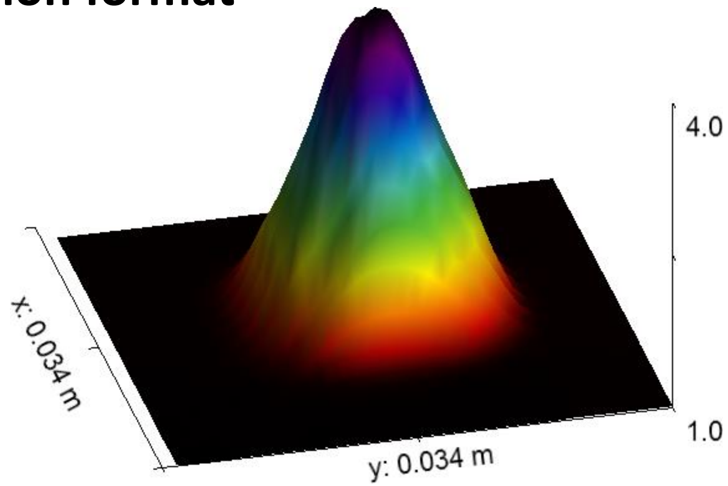
=> matrix 1681x1681 (step 1mm)

SUT laminate Rogers R4003 h=20mils (0.508 mm)

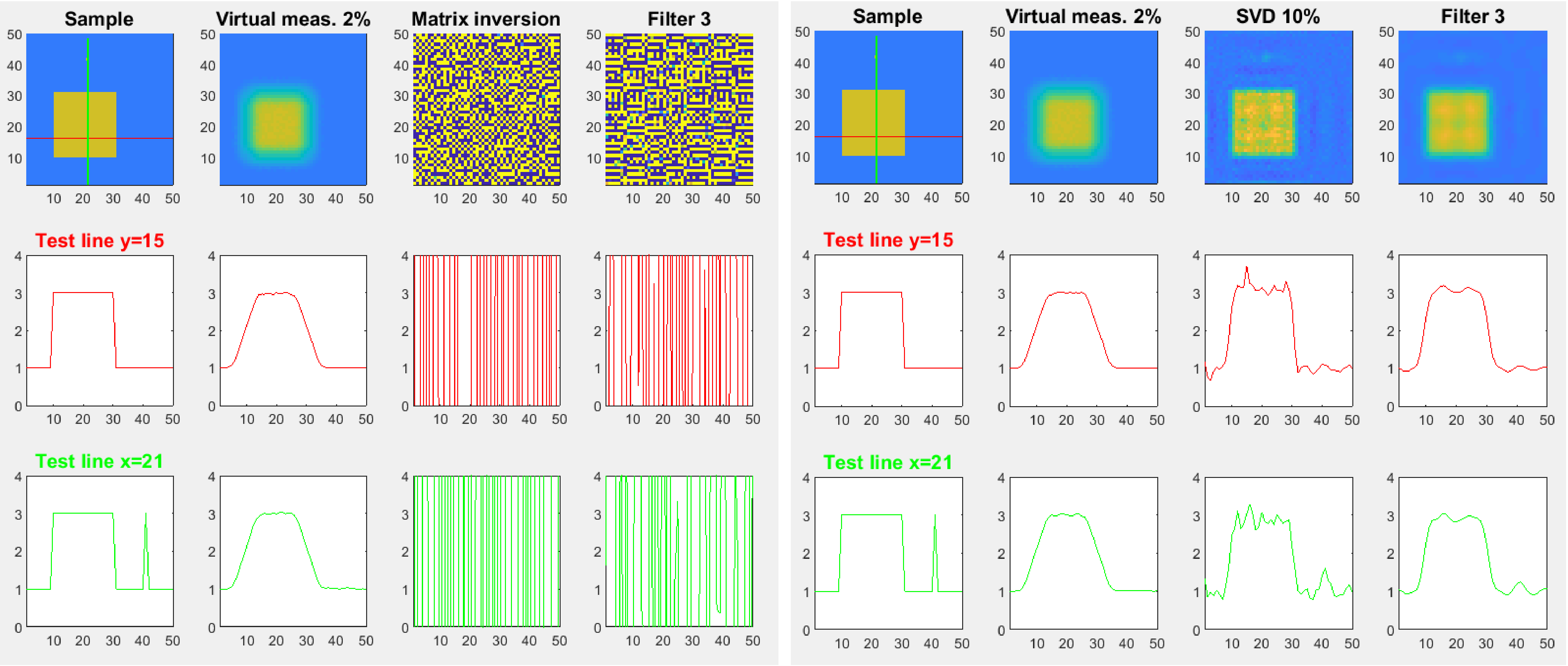
SUT size 15x15 mm

scan saved in Gwyddion format

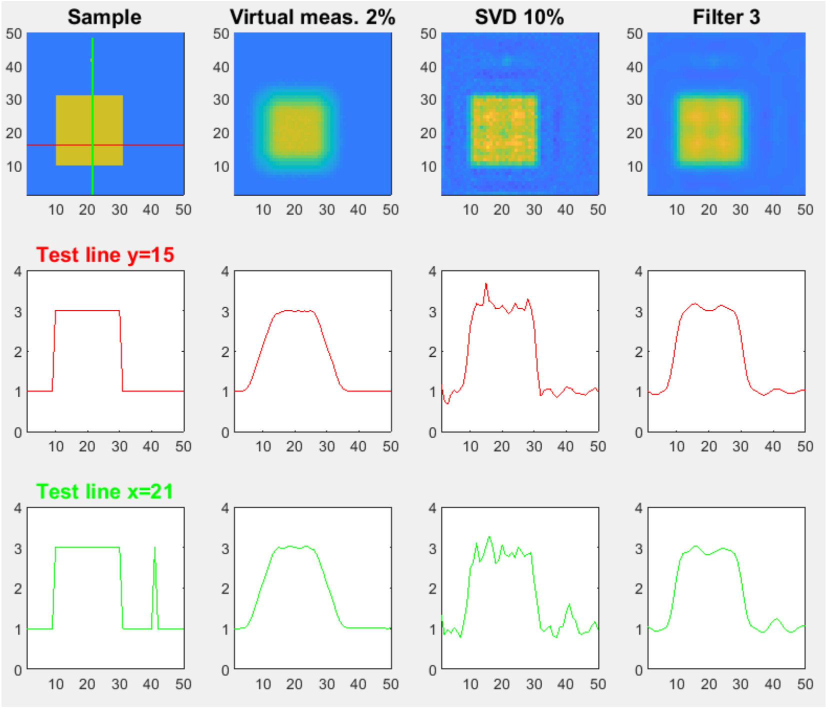


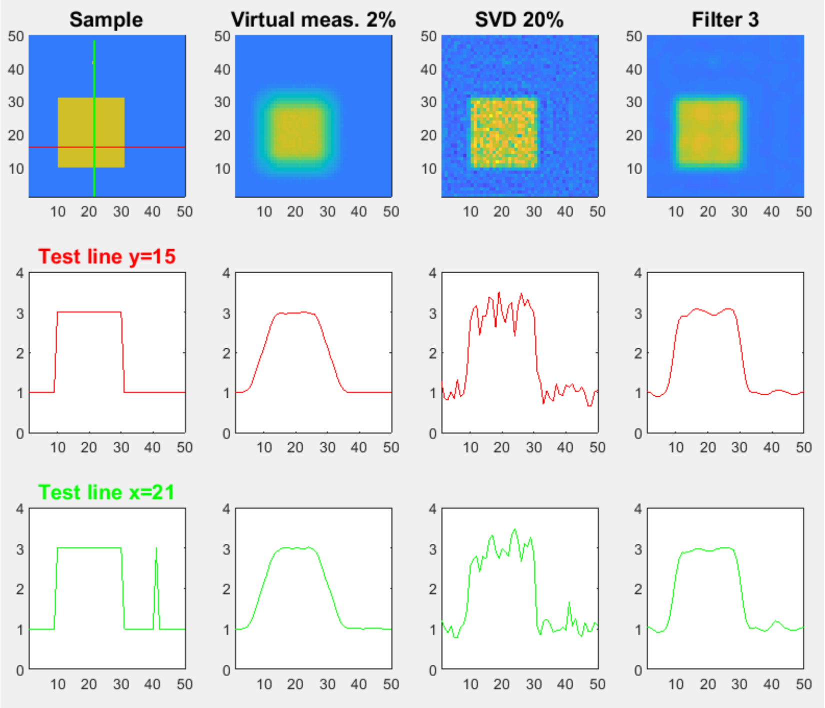


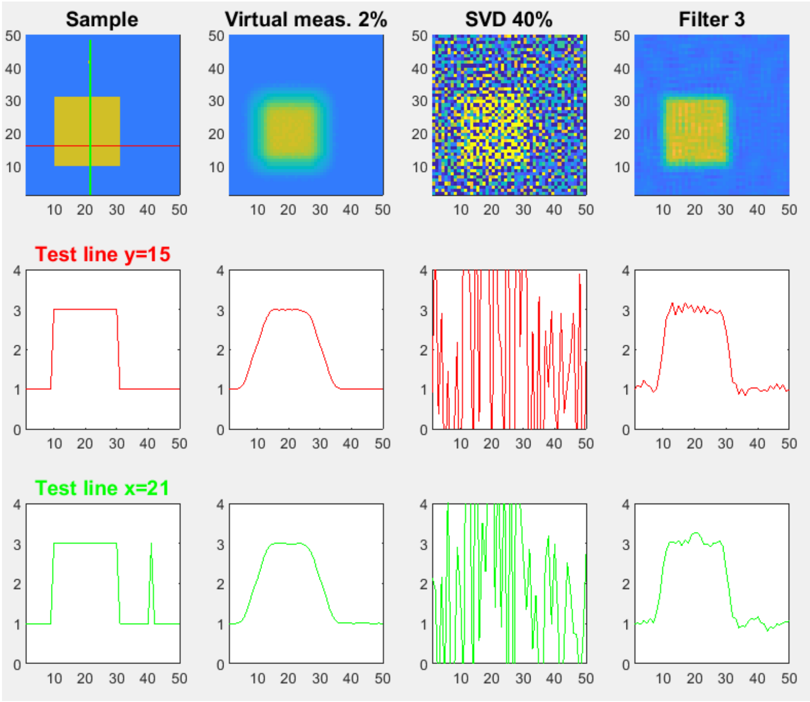
MATLAB experiments with virtual scans: matrix inversion versus SVD approach



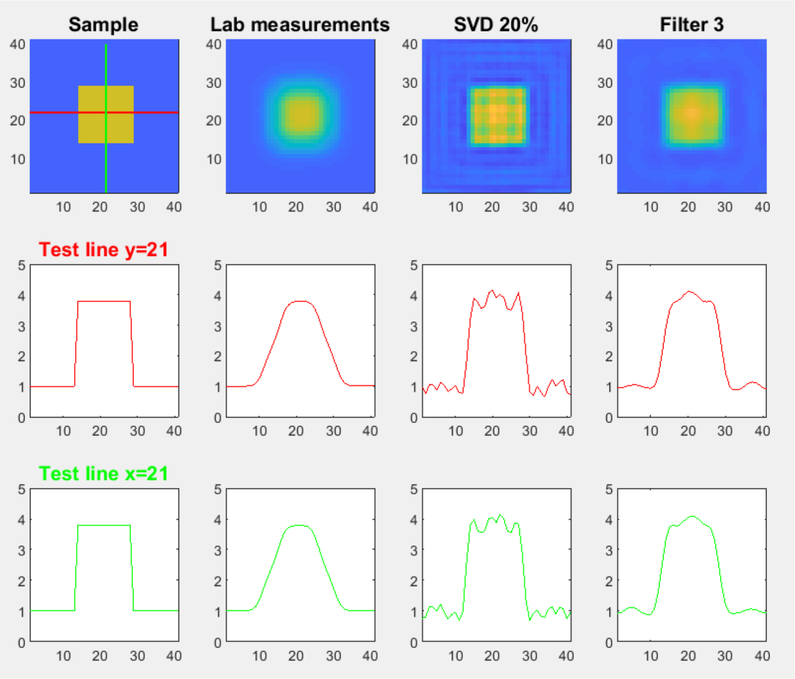
MATLAB experiments with virtual scans with error: experimenting with SVD parameters

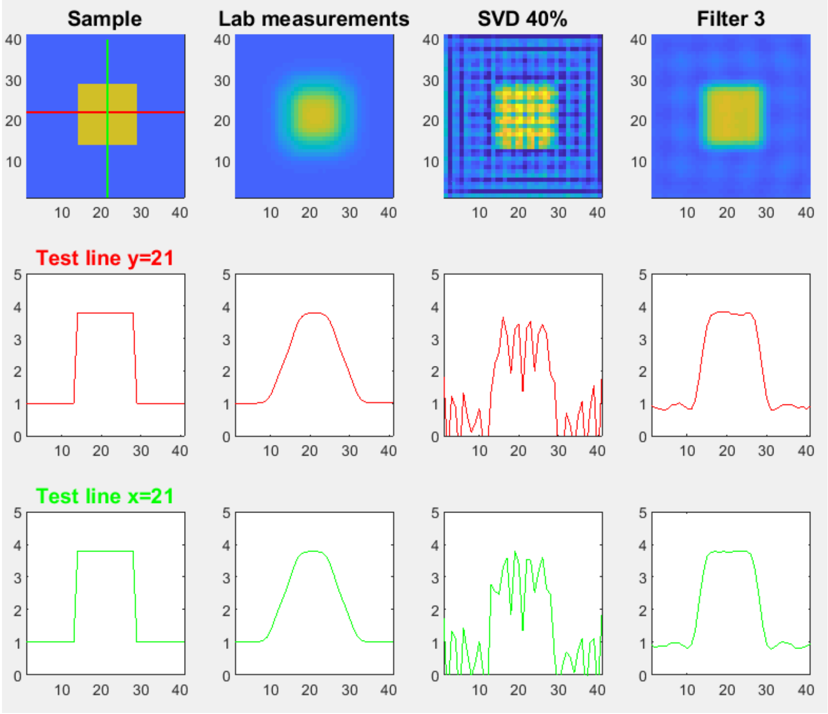


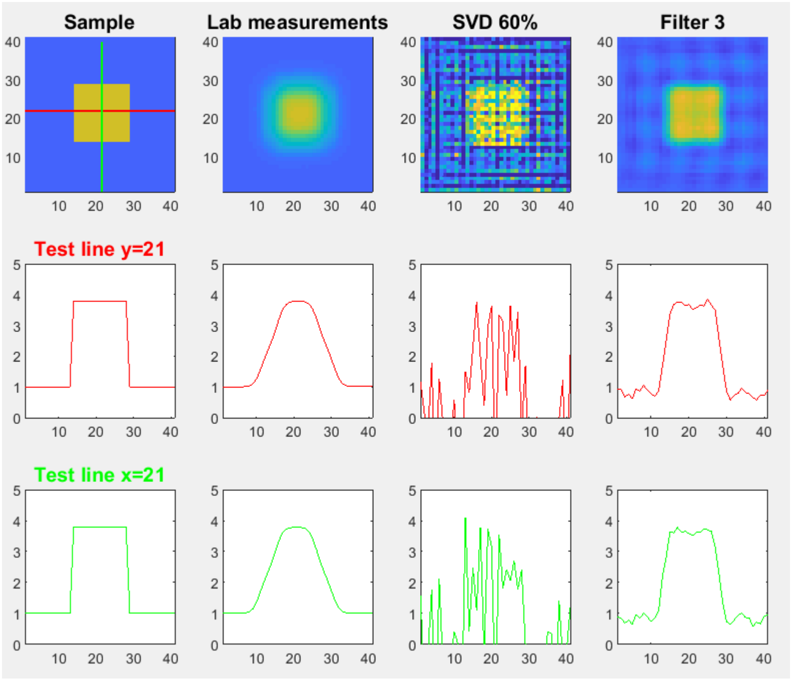


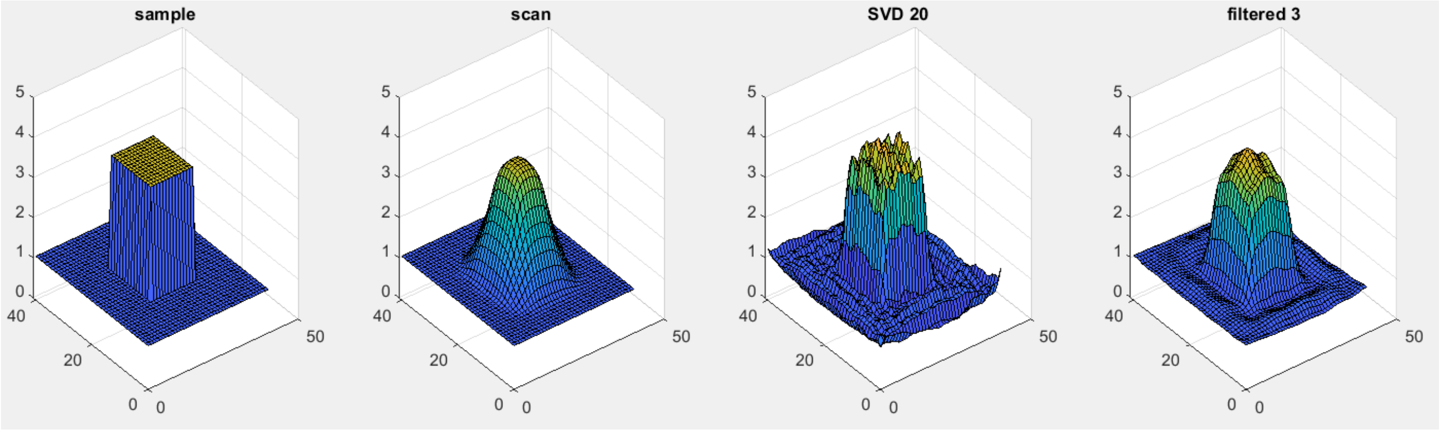


MATLAB experiments with laboratory scans: experimenting with SVD parameters

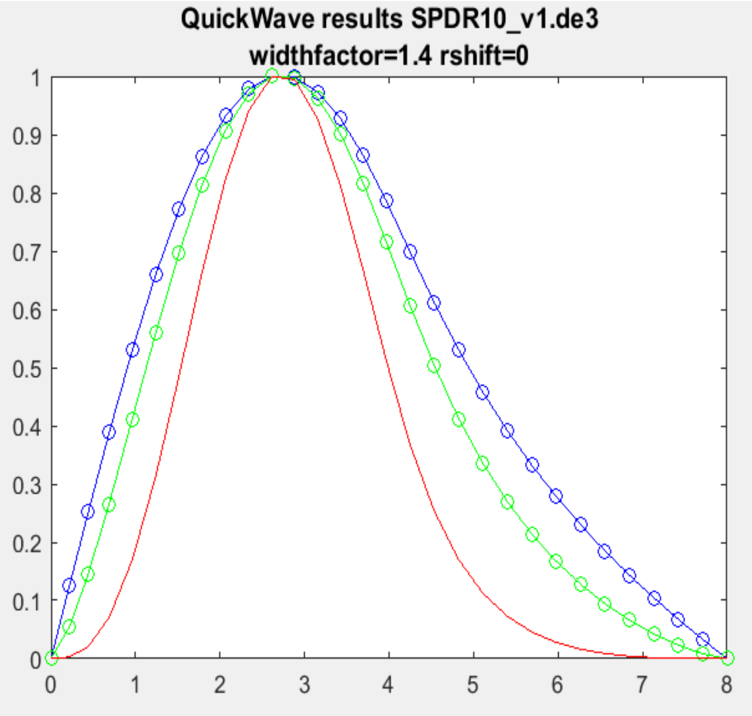


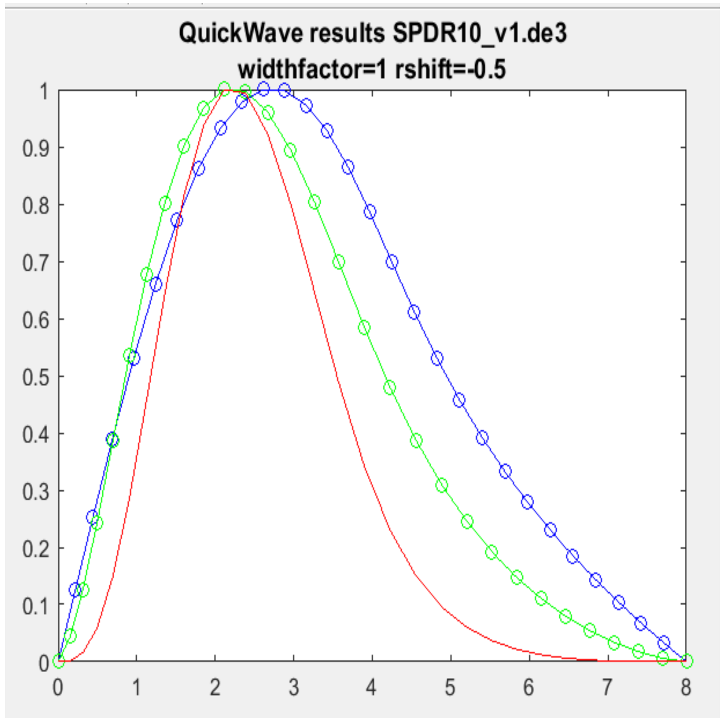


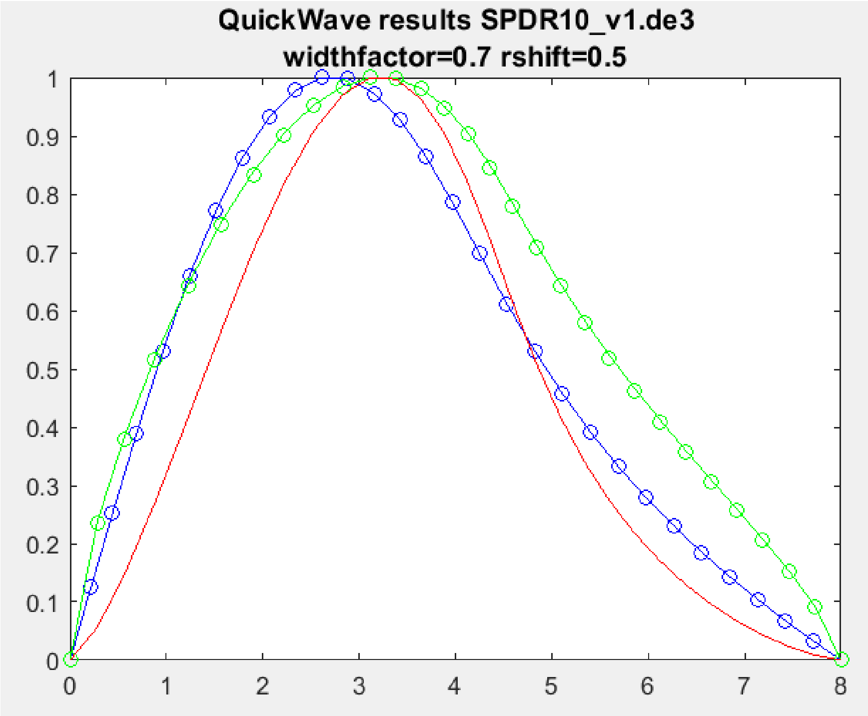




MATLAB experiments with laboratory scans: experimenting with templates







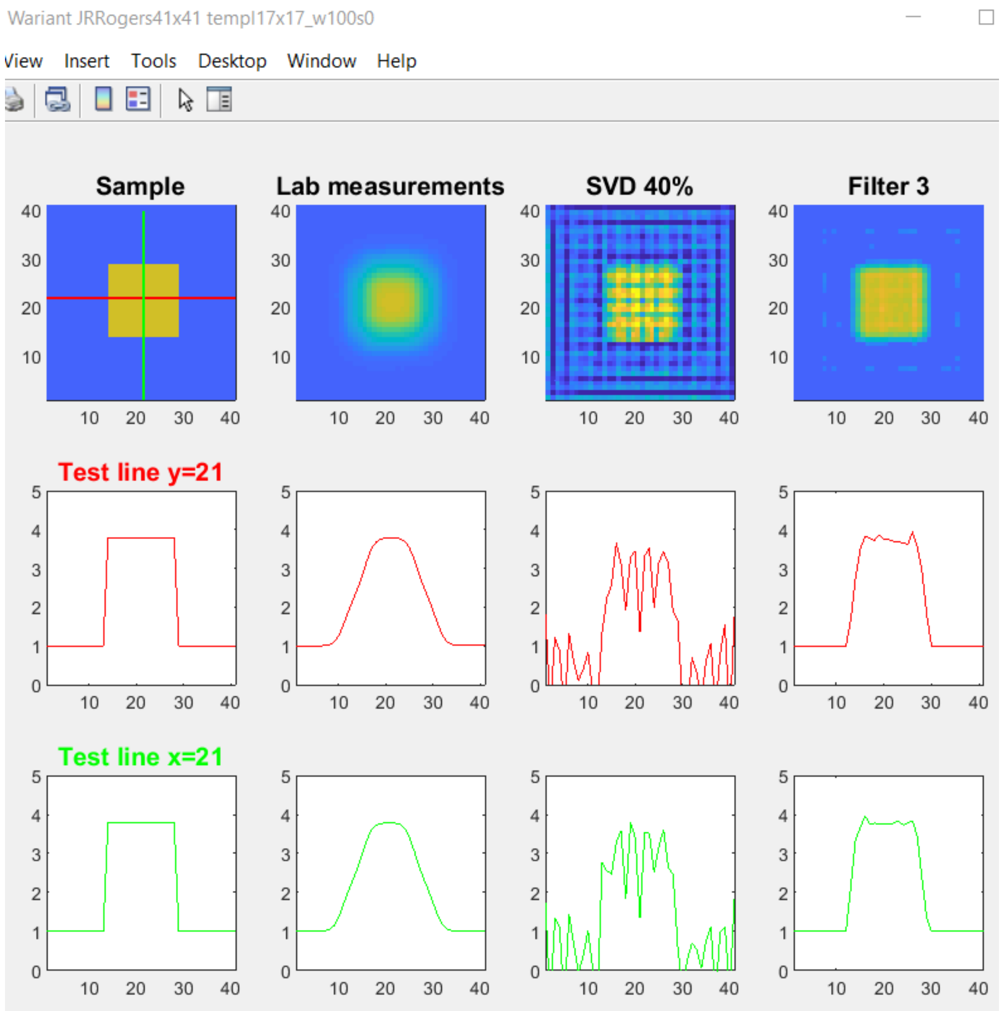
Note: each SPDR requires calibration -> field pattern after manufacturing differs from the theoretical design.

blue – QuickWave simulation of E-field for theoretical SPDR design, interpolated in MATLAB

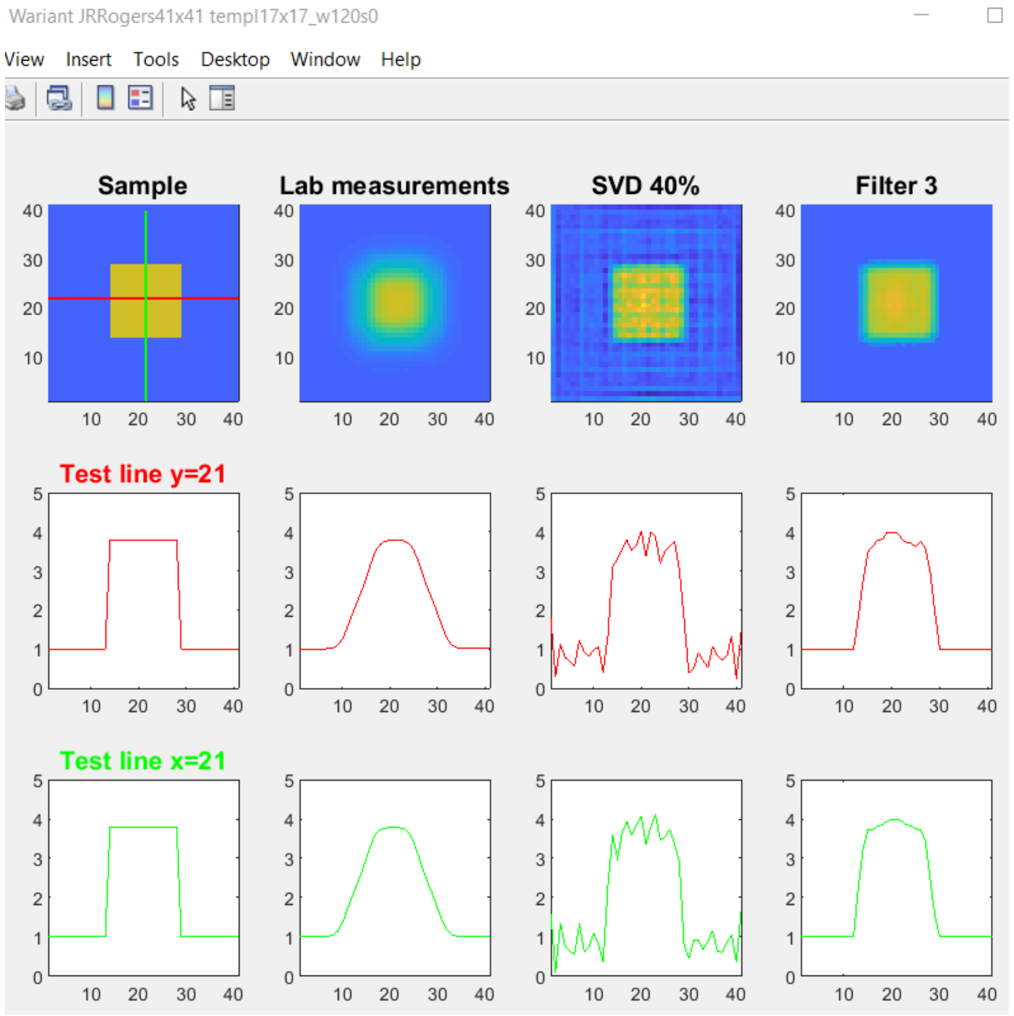
green – modified ("narrowing" or shift)

red – modified squared

MATLAB experiments with laboratory scans: experimenting with templates (1)

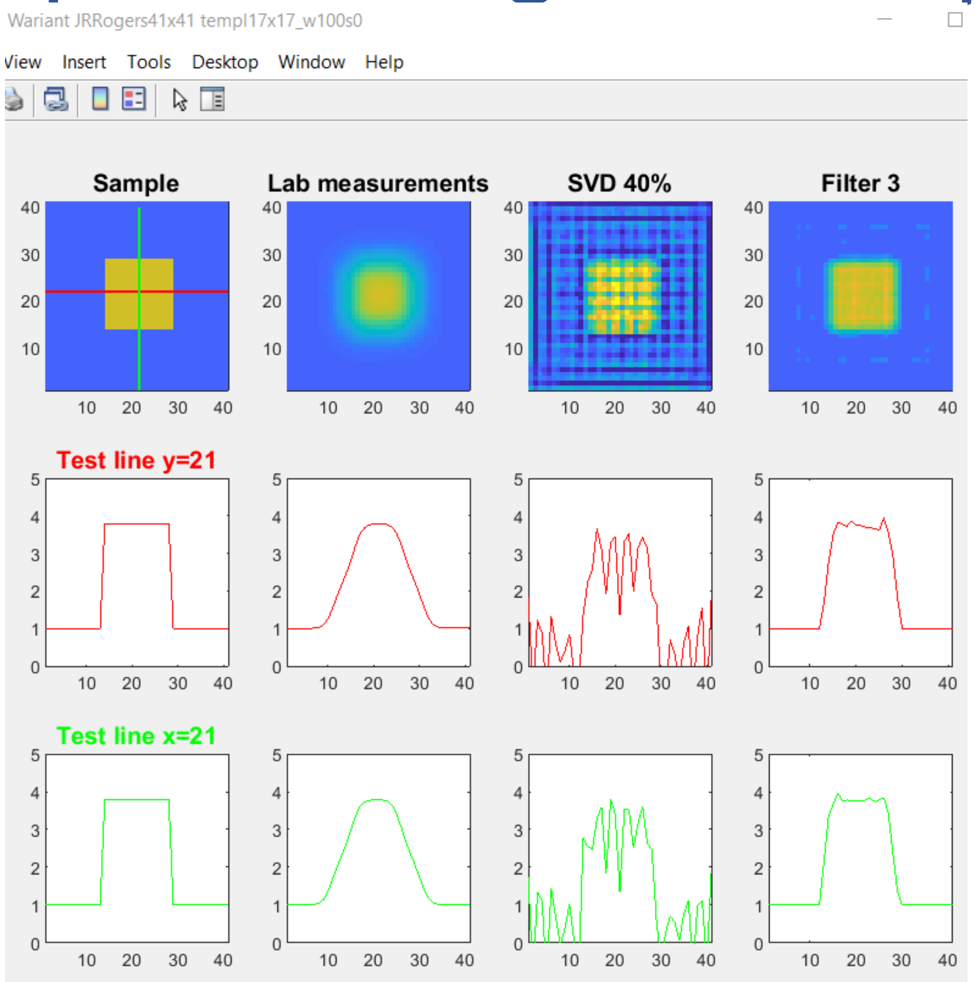


original template

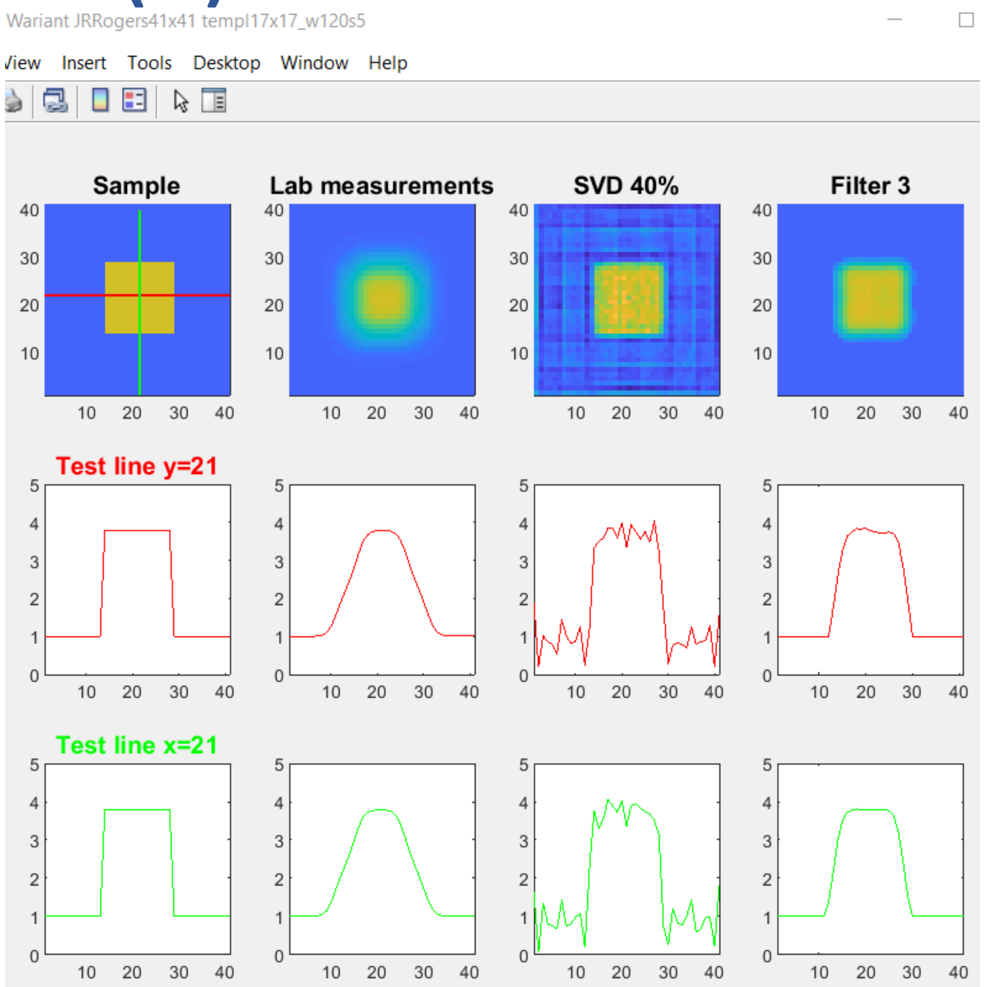


stronger energy concentration in ring: "narrower" template $E^{1.2}$

MATLAB experiments with laboratory scans: experimenting with templates (2)



original template

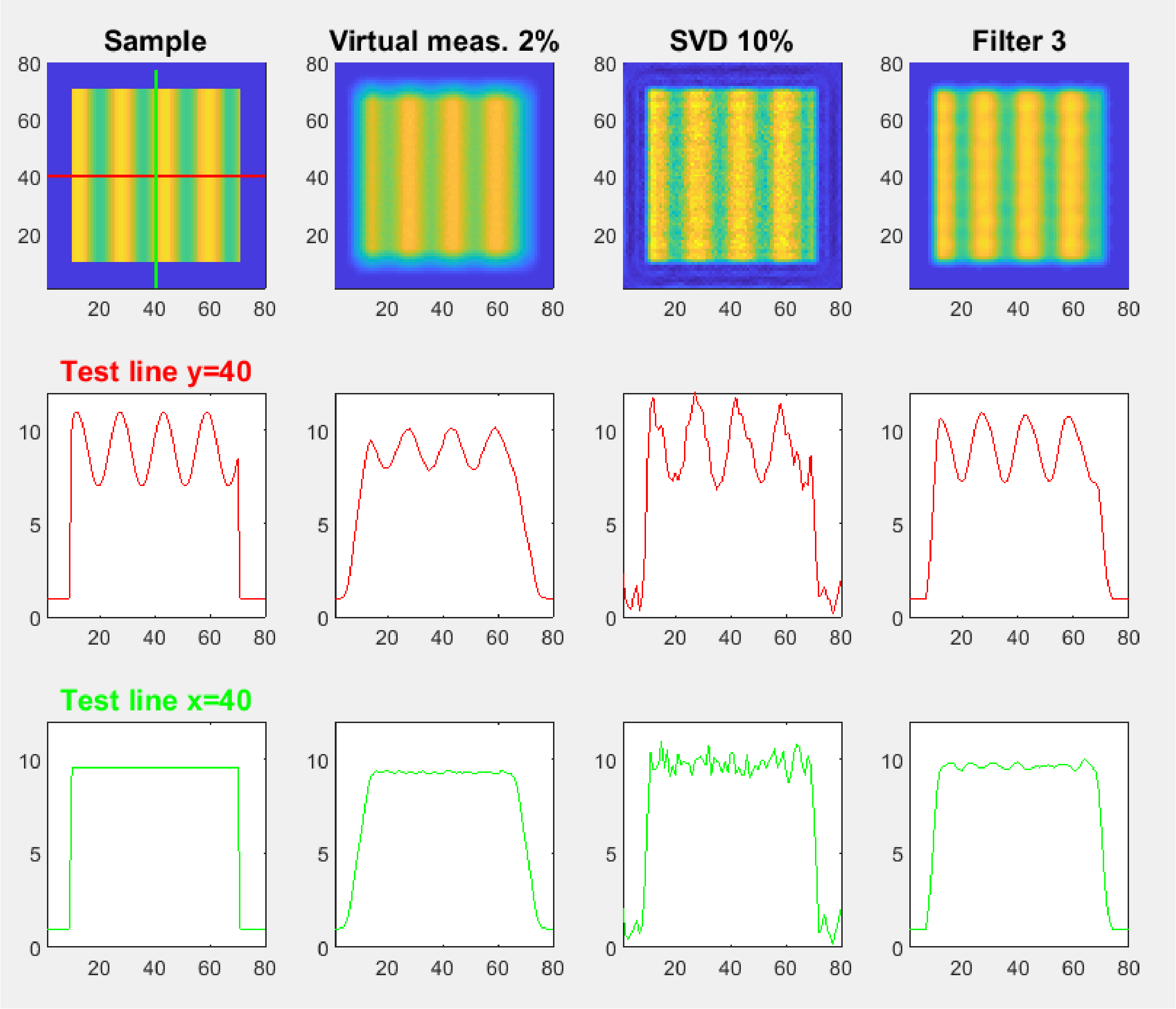


"narrower" template

stronger energy concentration in ring: template $E^{1.2}$

further shifted by 0.05 mm

MATLAB experiments with virtual scan: continuous permittivity distribution



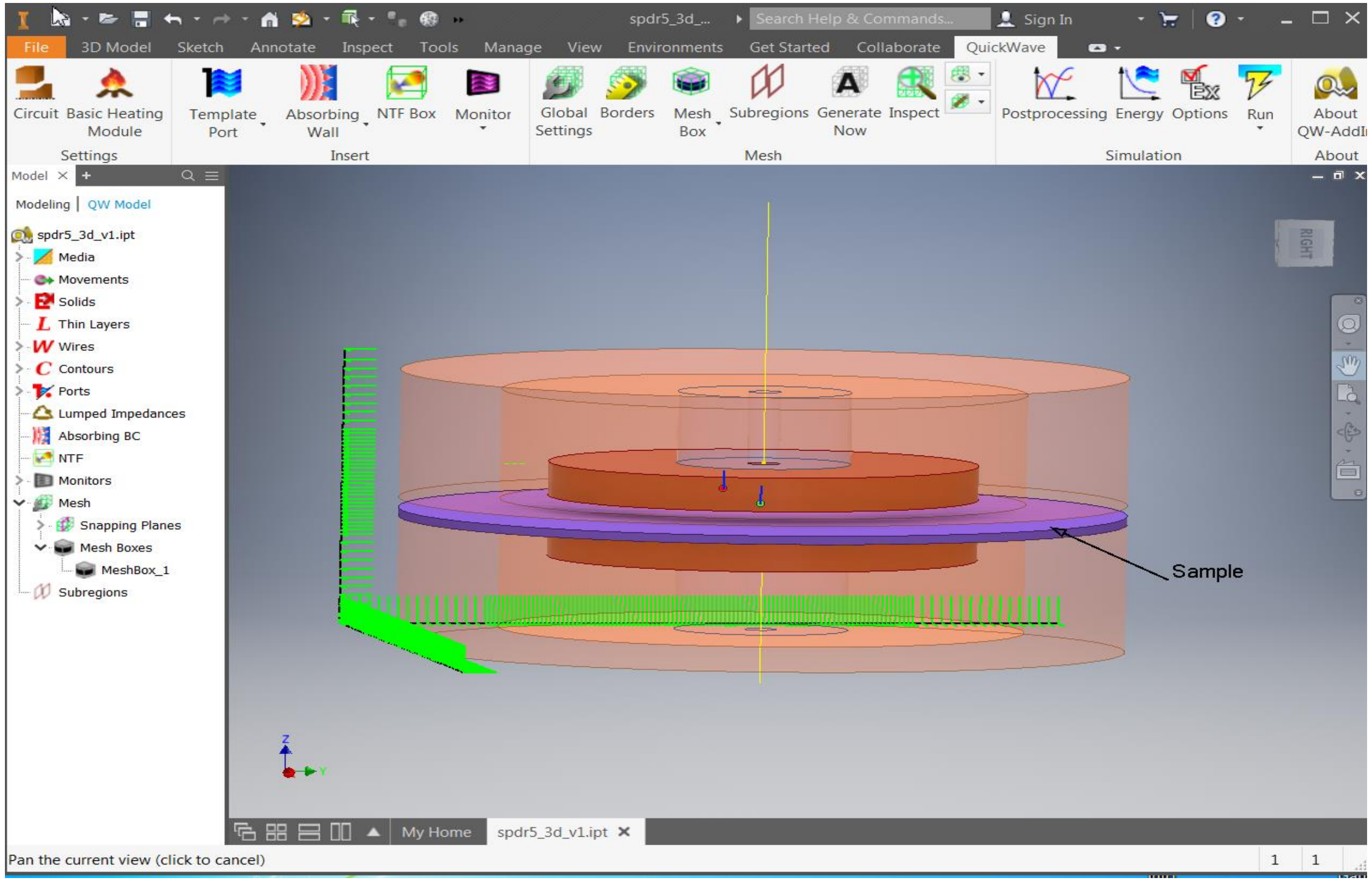
Virtual permittivity pattern, corresponding to radial resistivity pattern measured on wafer.

Different resolution criteria in two driections:
horizontal – continuous pattern
vertical – sharp edges;
both enhanced with SVD method.

Modelling validation of SPDR method assumptions

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

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



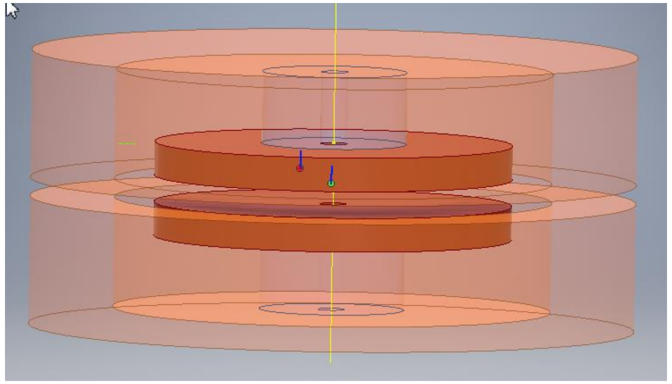
10 GHz SPDR model in QW-AddIn for Autodesk® Inventor® Software

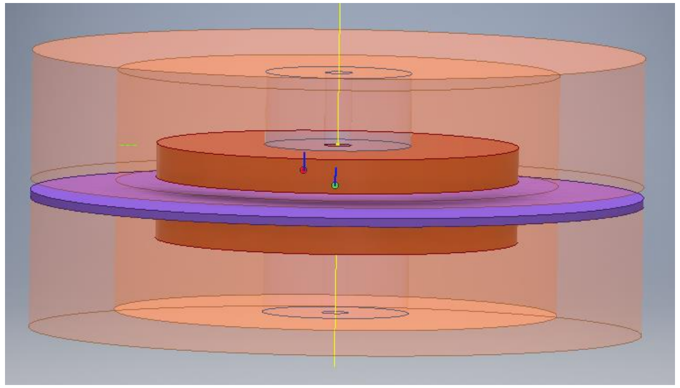
Modelling validation of SPDR method assumptions

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

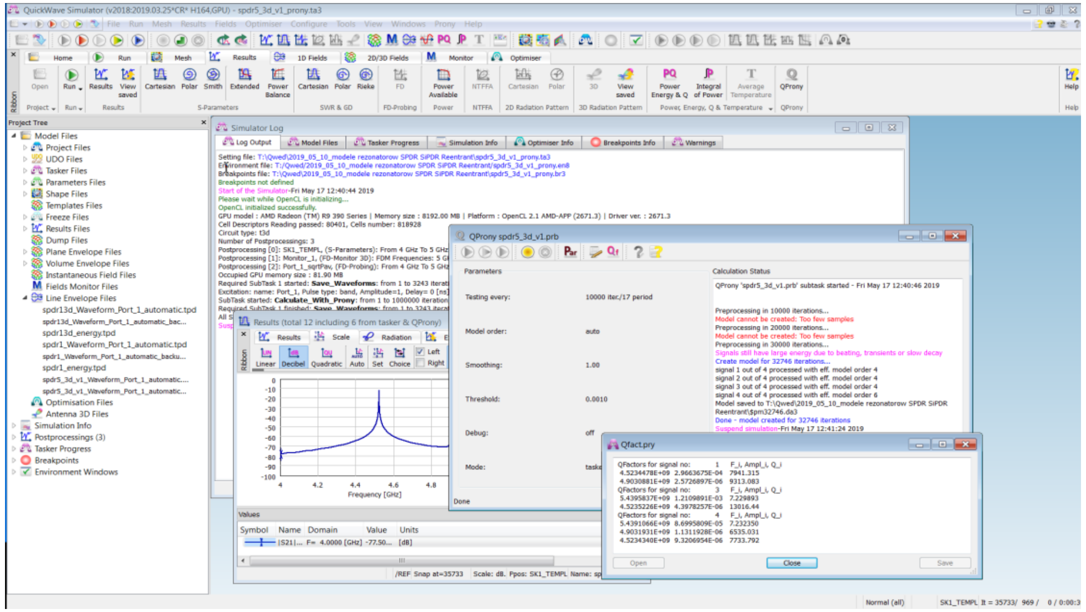
→ application of "*near field imaging*" in QuickWave

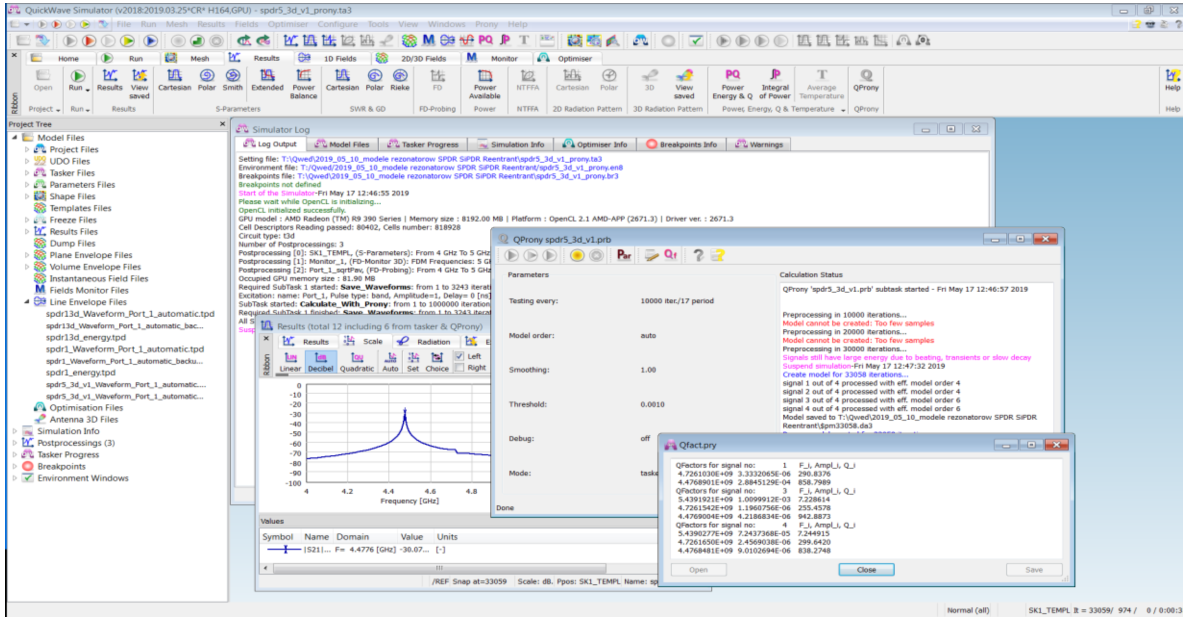
empty





with SUT

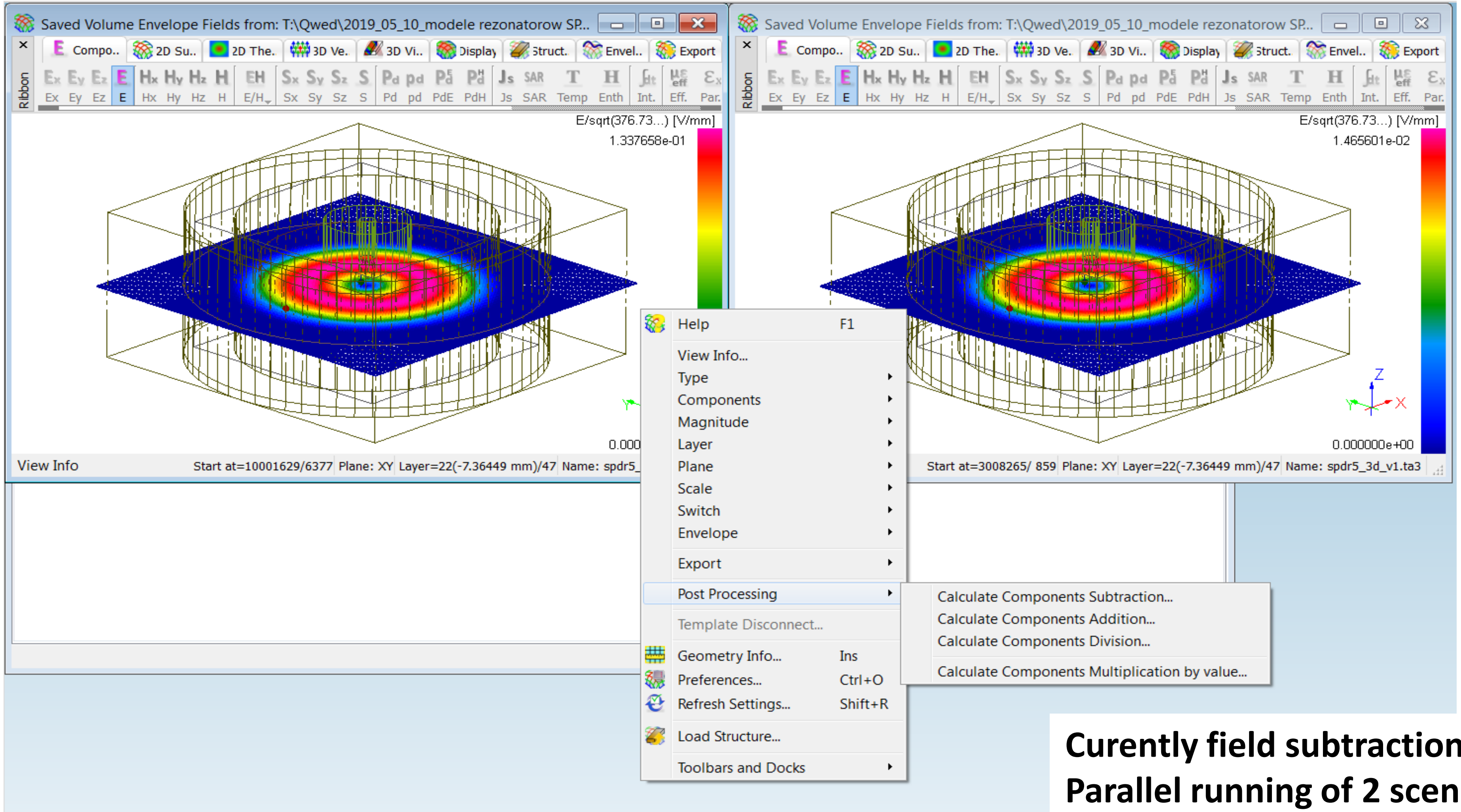




Modelling validation of SPDR method assumptions

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

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

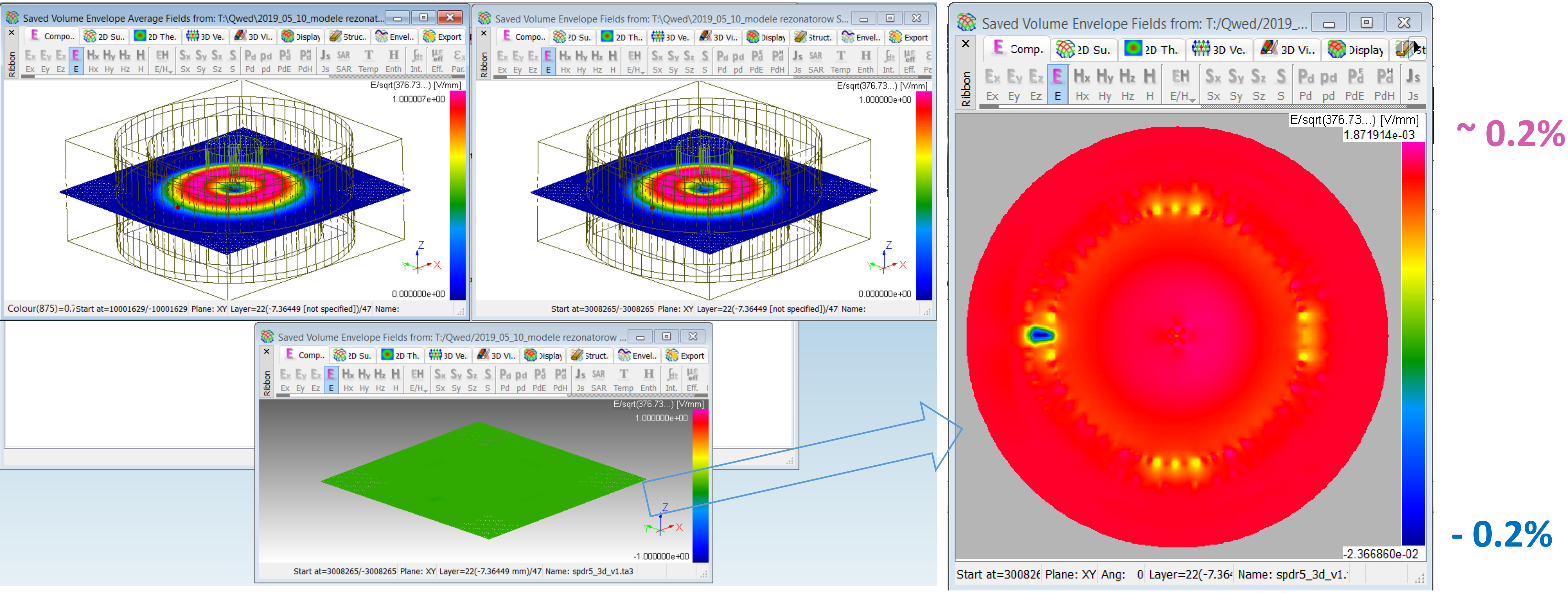


Curently field subtraction performed on saved fields.
Parallel running of 2 scenarios under development.

Modelling validation of SPDR method assumptions

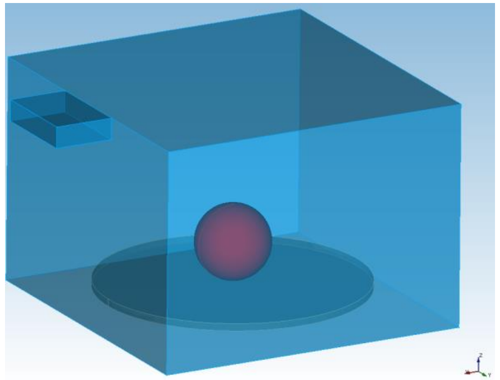
How much is the E-field pattern influenced by SUT?

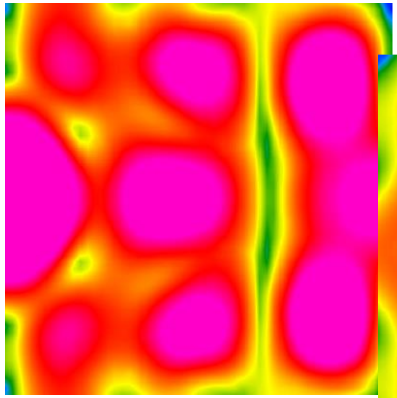
→ application of "*near field imaging*" in QuickWave



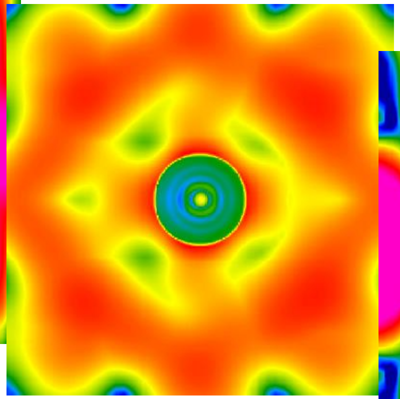
Advanced near-field imaging functionality

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

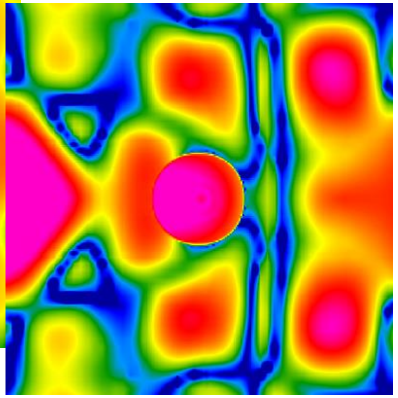




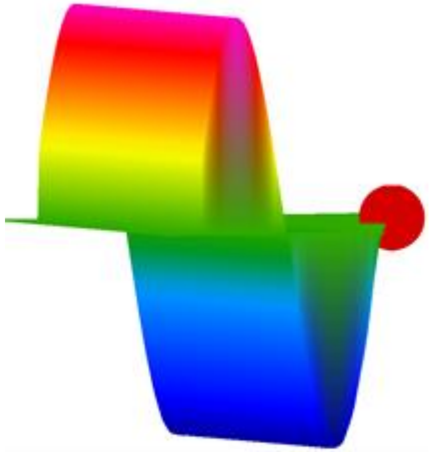
E-field in an empty cavity

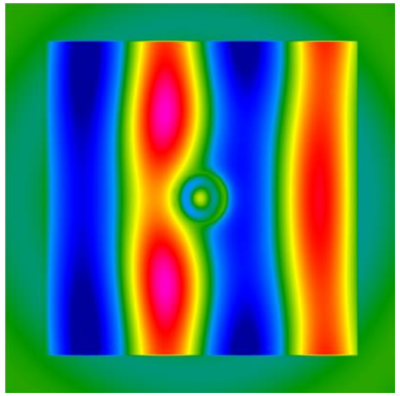


E-field in a loaded cavity

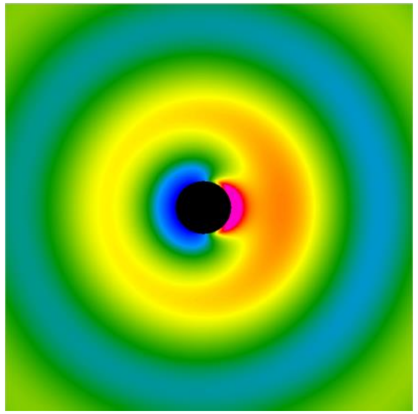


Scattered near-filed in cavity



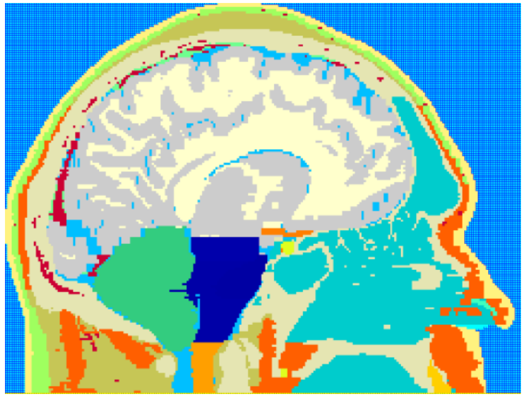


Total field
Focusing by the load
„exploding egg effect”

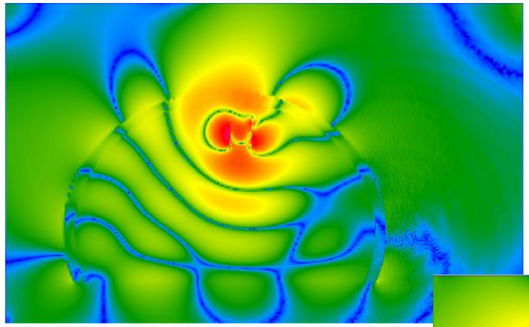


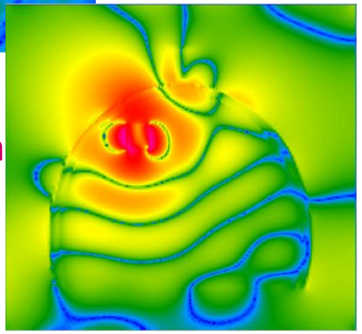
Diffracted field reveals cause of focusing: circumferential resonance

Detection of inhomogenities in tissues



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





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

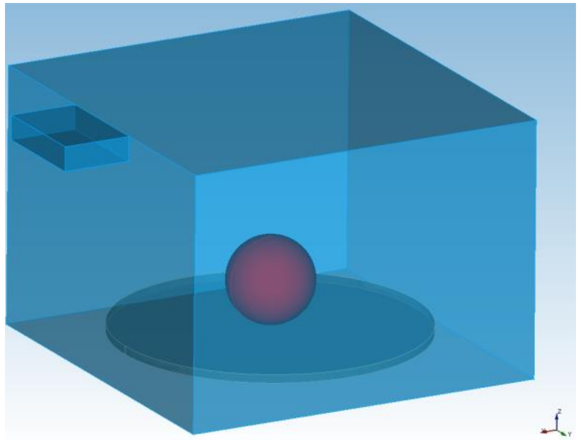
* https://sites.utexas.edu/austinmanaustinwomanmodels/

Accurate modelling of coupled electromagnetic-thermal problems

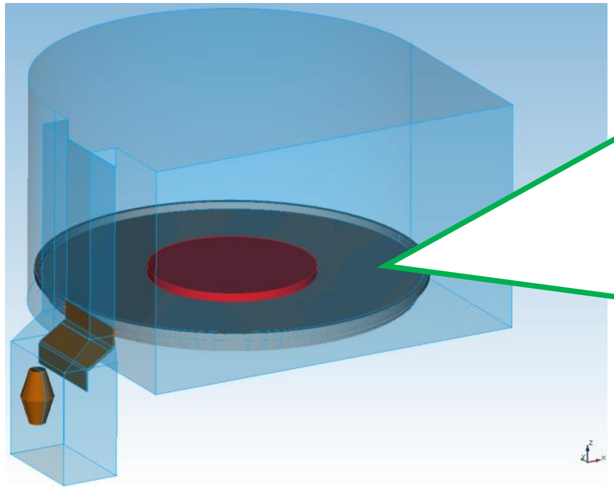
Application to

Simple microwave heating benchmarks & microwave heating phenomena studies*

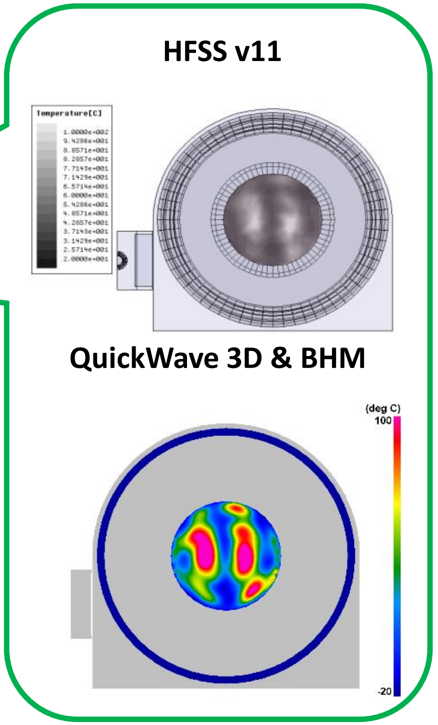
Design & analysis of real-life microwave oven cavities, incl. complicated cavity shapes and advanced feeding system*



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

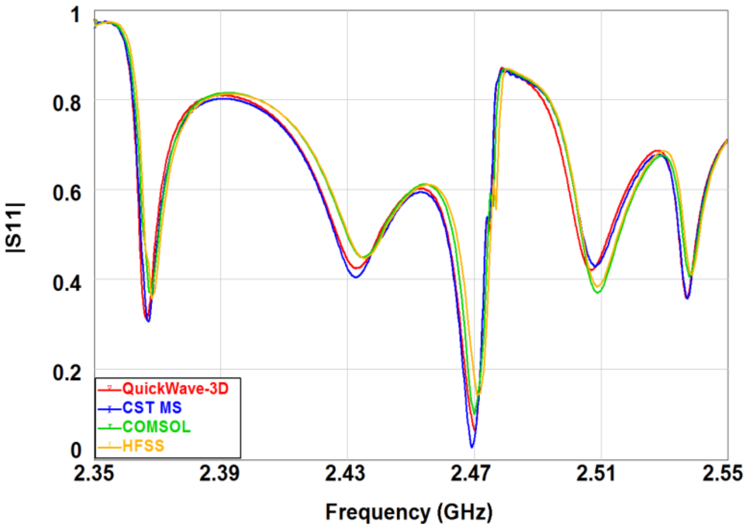


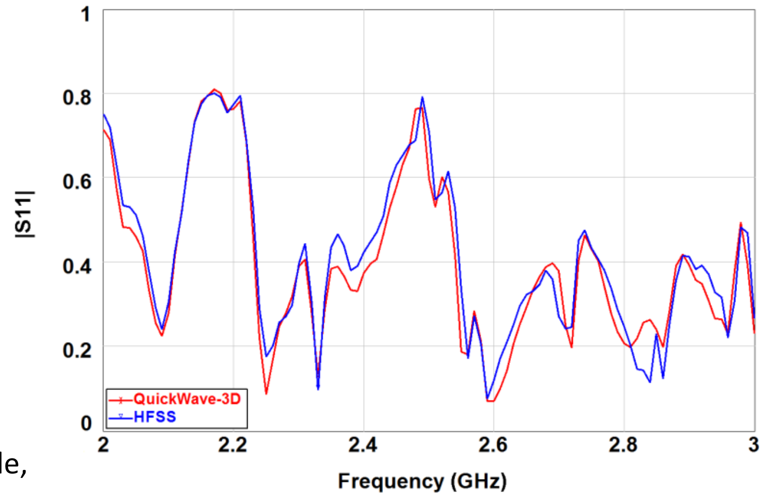
Courtesy of Whirlpool Inc. – Whirlpool MAX oven



Freezing to file the state of the simulation

De-freezing on arbitrary computer & at convenient time

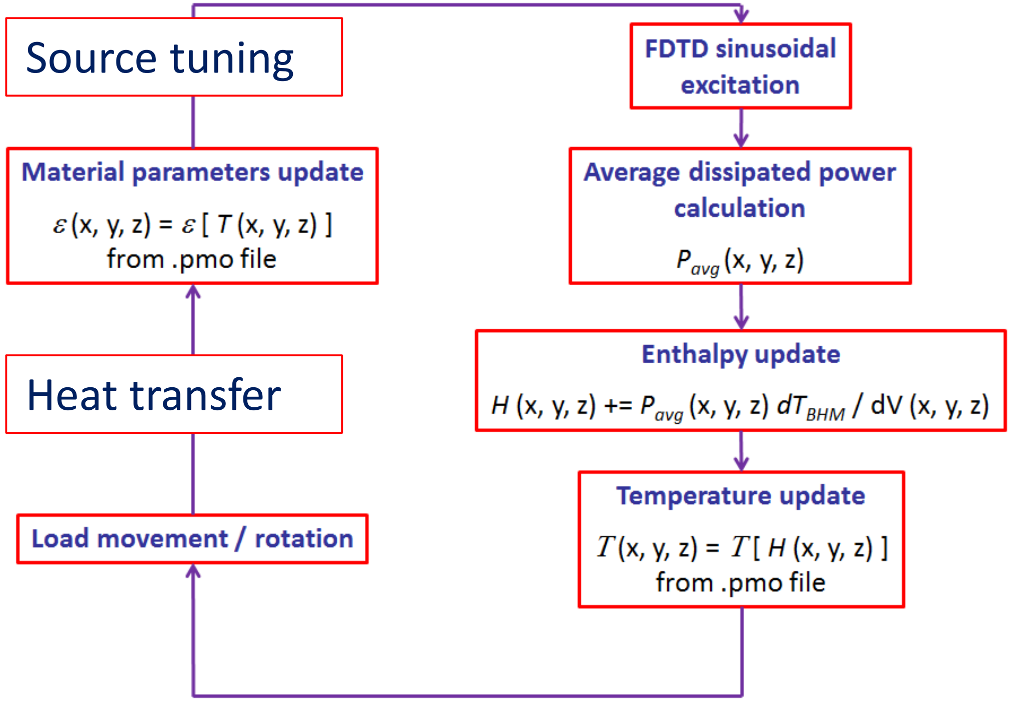


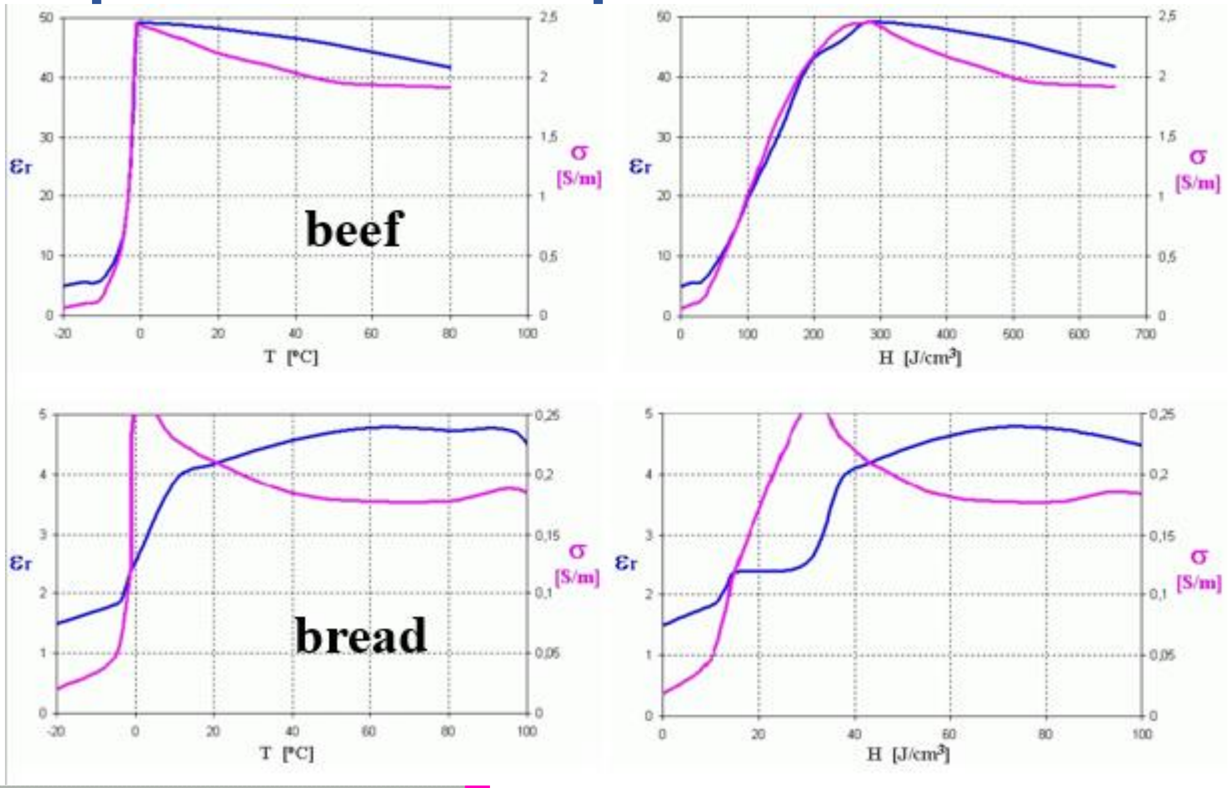


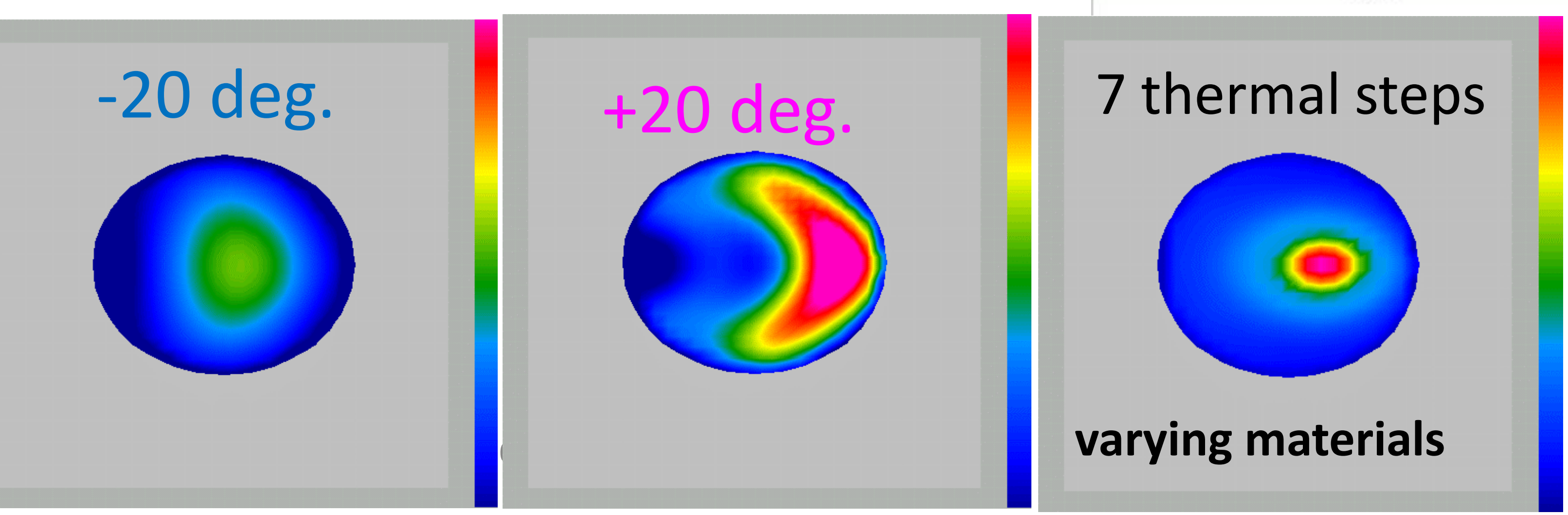
With QuickWave EM computation as fast as **1 min 18s** on a **low-cost video card** – supporting **all** graphic cards **with OpenCL**

* 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: temperature-dependent materials





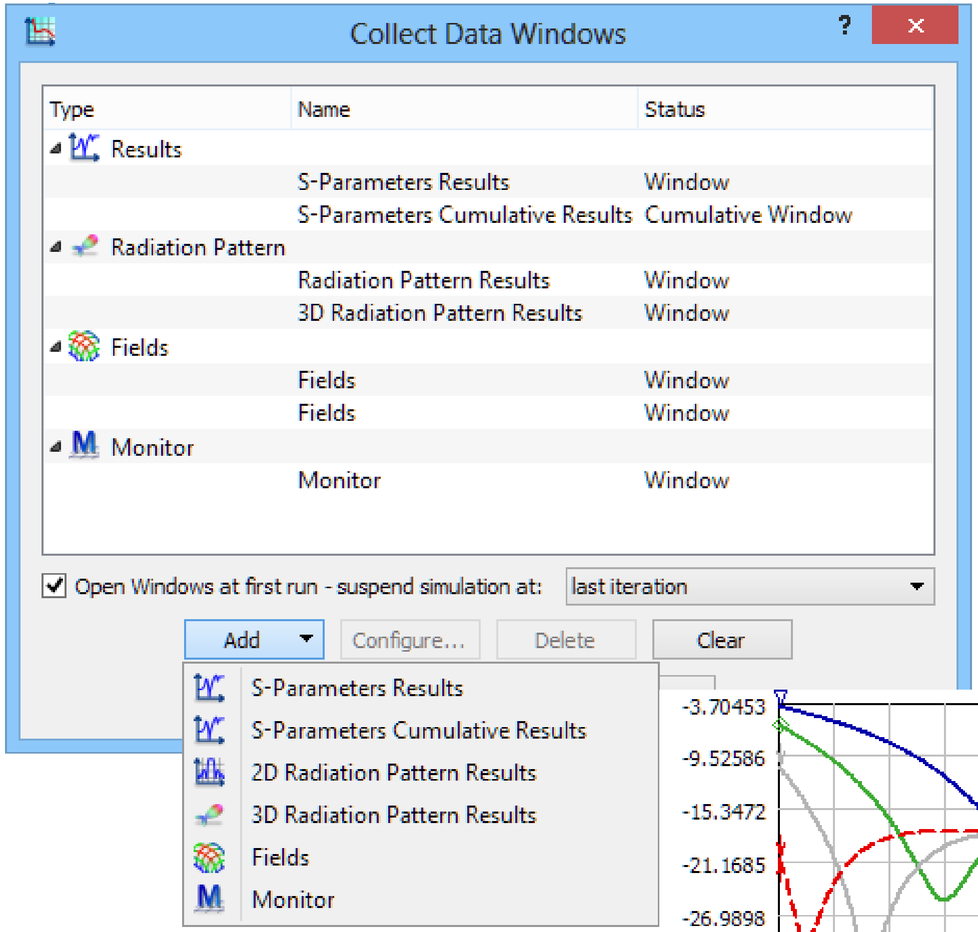


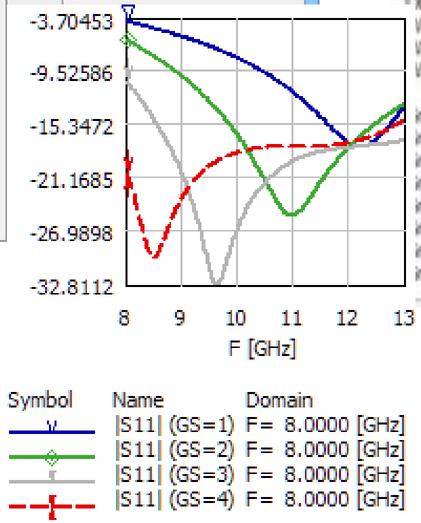
QW-BHM module of QuickWave:

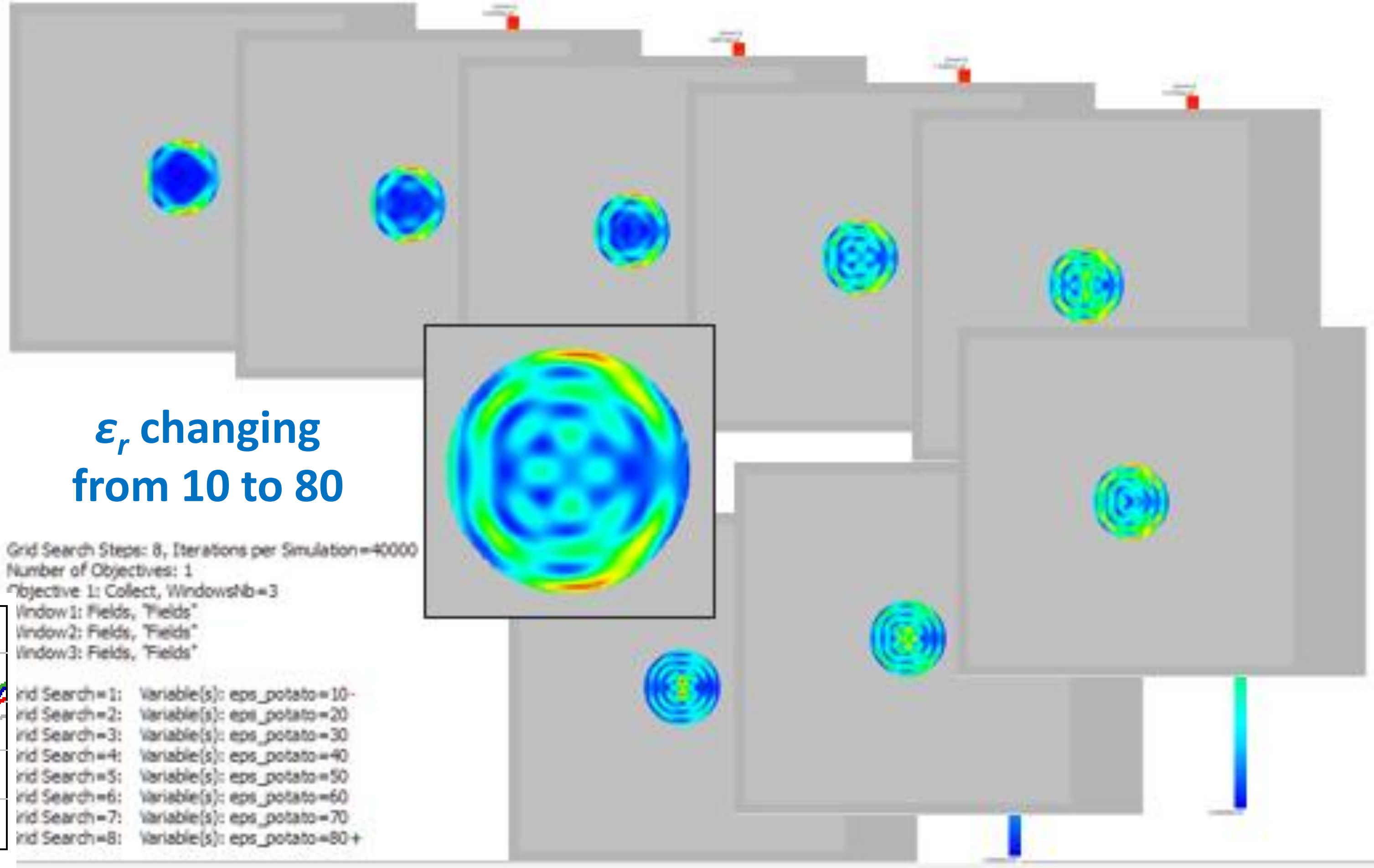
- **automatic system**
- **each cell heated individually**
- **no need to define 1000s of "media"**
- **bilateral coupling EM - thermal**

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

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

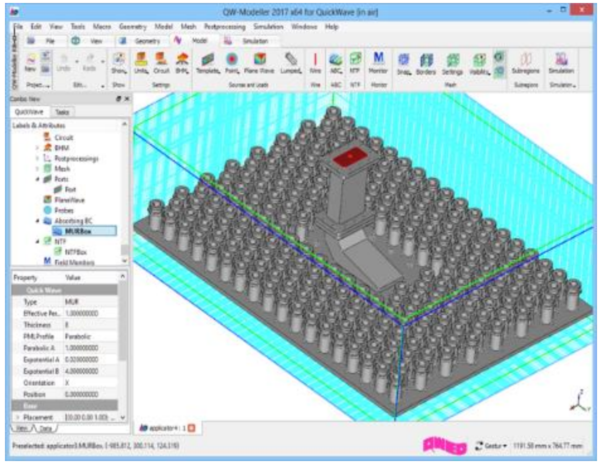
Note: automatic multiple switching from pulse to sine excitation implemented in QuickWave for matching source to load.

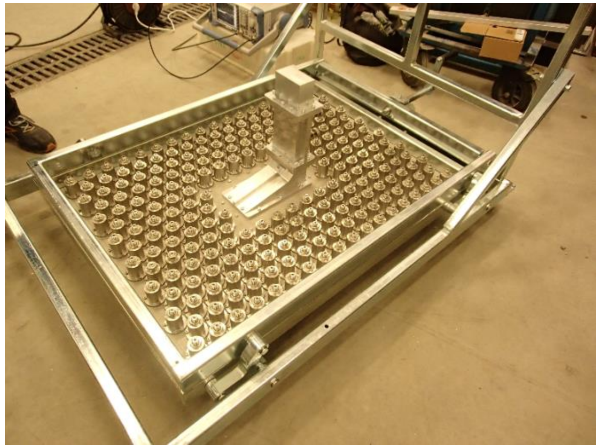
Unusual QuickWave applications

High power applicator for µW treatment of bituminous surfaces aiming at road repair

Challenges

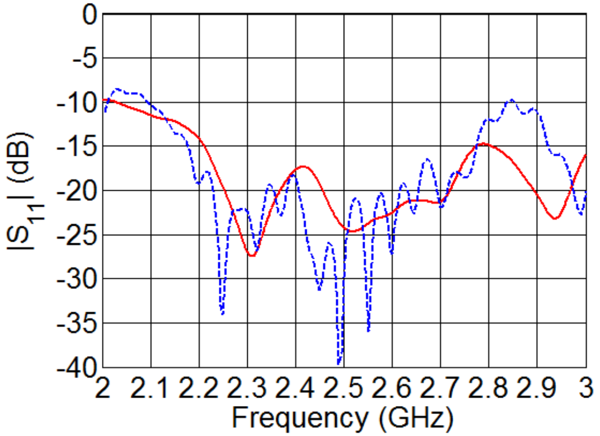
- High dissipation of µW power in road surface
- Safety issues – prevention of EM energy leakage



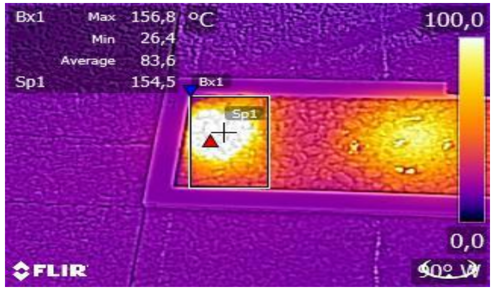


High power applicator with a system of chokes preventing µW energy leakage

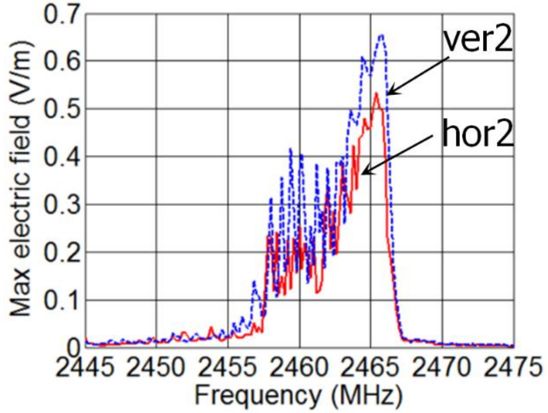
Simulated & measured reflection coefficient



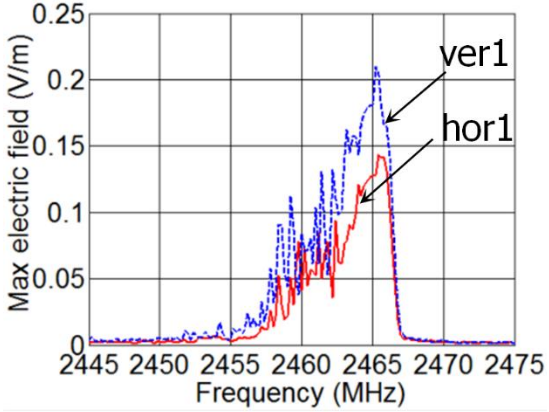
Measured temperature distribution



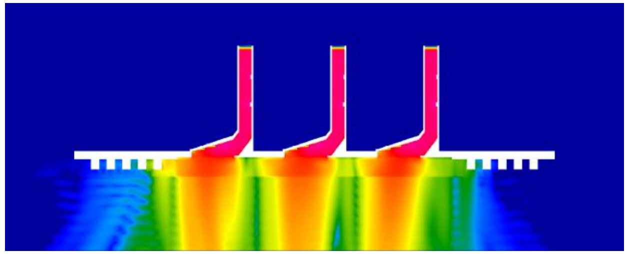
Exposure levels @ 0.5m from applicator
Below standardized limits

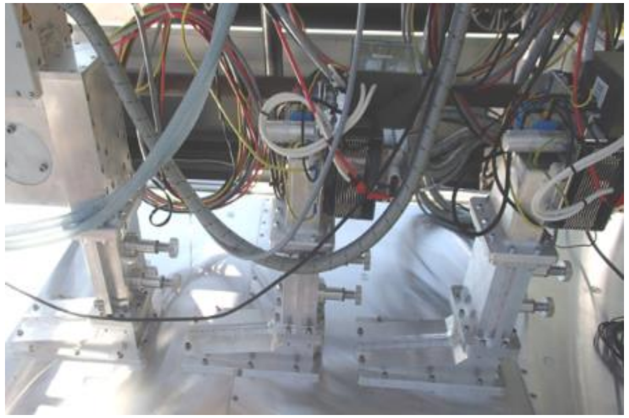


On a side



In front

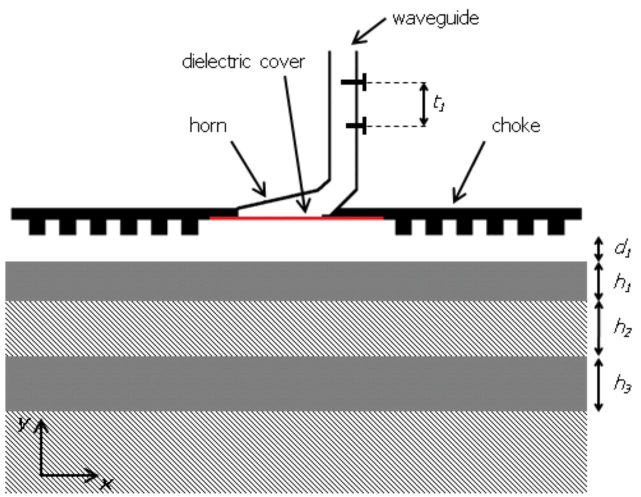


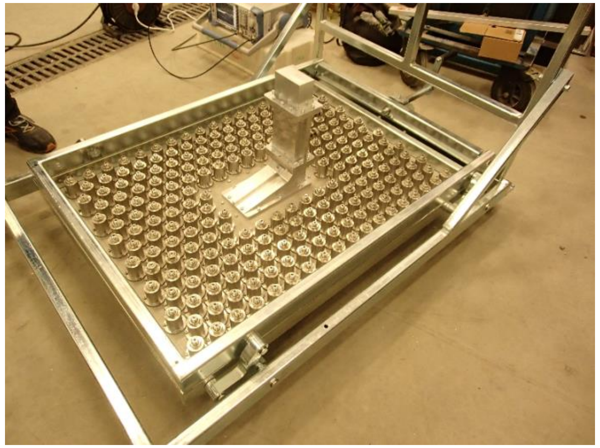


System of three MW power applicators with feeding system and leakage preventing chokes: designed, manufactured, tested

B. Salski, M. Olszewska-Placha, T. Karpisz, J. Rudnicki, W. Gwarek, M. Maliszewski, A. Zofka, J. Skulski, "Microwave applicator for thermal treatment of bituminous surfaces", *IEEE MTT Trans.*, vol. 65, no. 99, pp. 1-9, 2017

Advanced optimisation and parameters sweep regimes





Microwave applicator for thermal treatment of bituminous surfaces

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

Internal optimisation

Optimisation with external tools – commercial and in-house

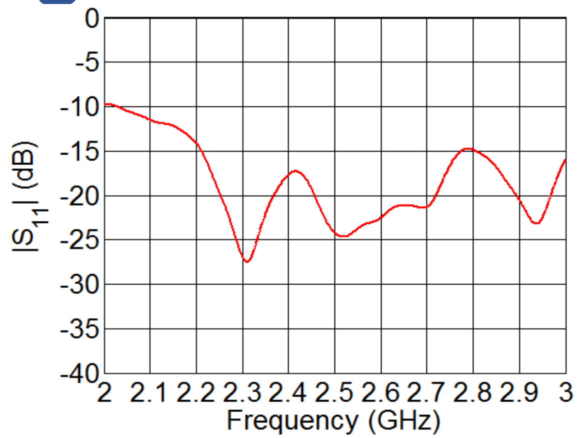
Typical, software predefined optimization objectives, e.g. S-parameters, Radiation patterns (incl. fit under user-defined radiation envelope), etc.

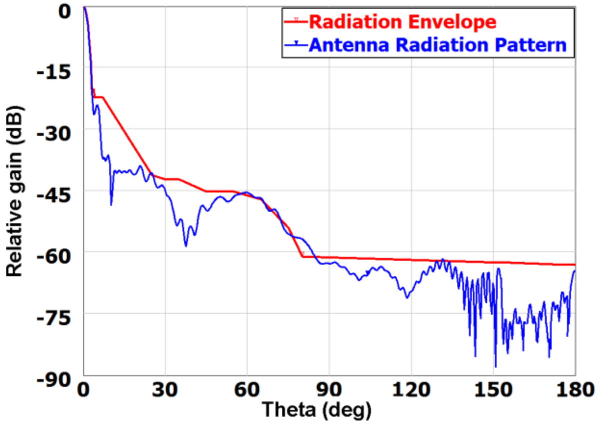
All simulation available objectives, e.g. power dissipated, shielding effectiveness, radiation efficiency, etc., through external data-extraction application

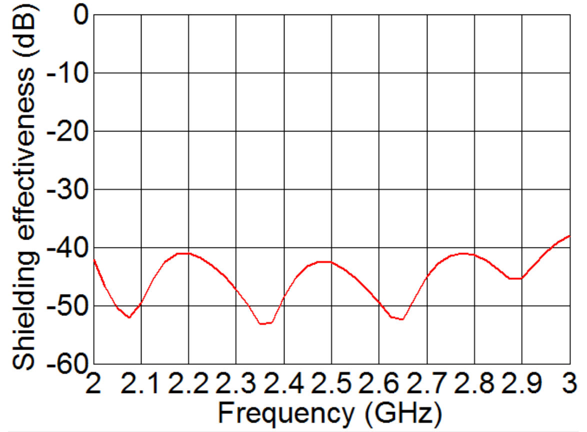
Simulation results saved to file

External application – objective extraction from file

Optimiser – internal or external

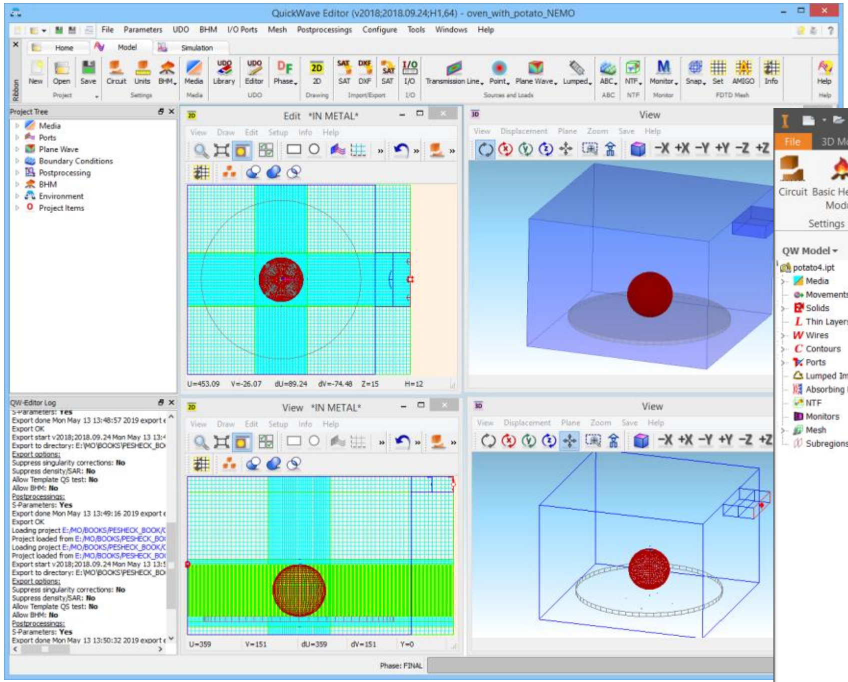






Dedicated user interfaces for parametrised project creation

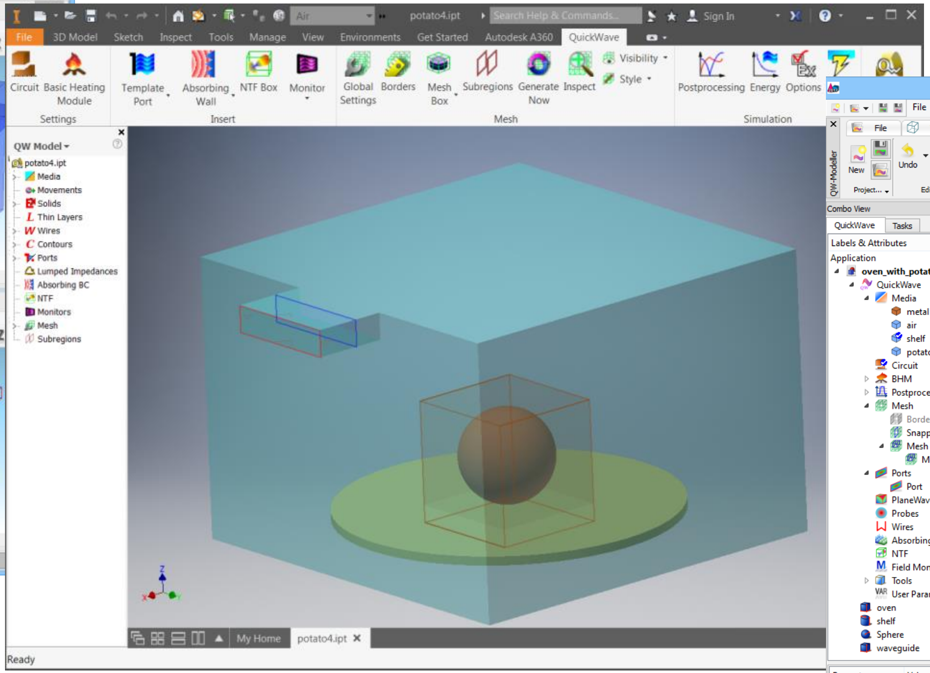
QW-Editor



In-house, script based

Import/export to *.sat & *.dxf

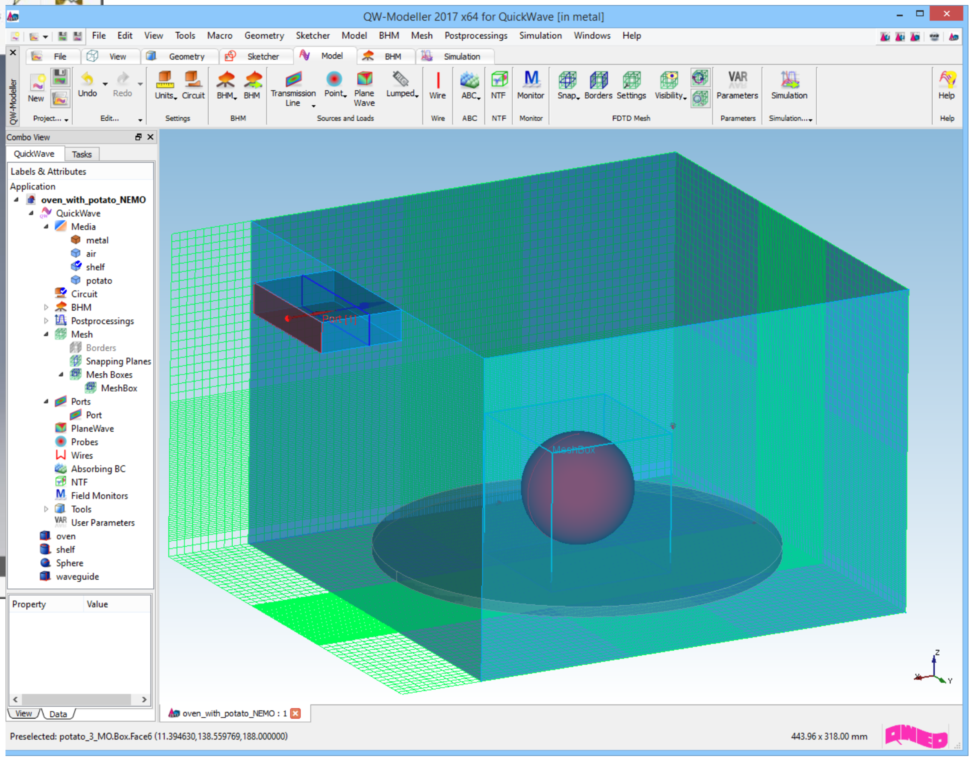
QW-AddIn for Autodesk Inventor Software



Based on advanced professional CAD tool

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

QW-Modeller



CAD tool - FreeCAD based

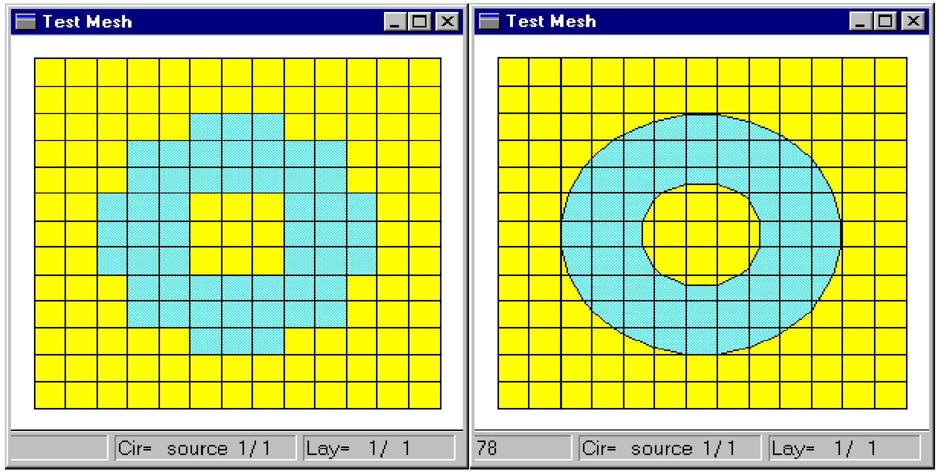
Free of charge, No licences, No time restrictions, No project limitations

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.

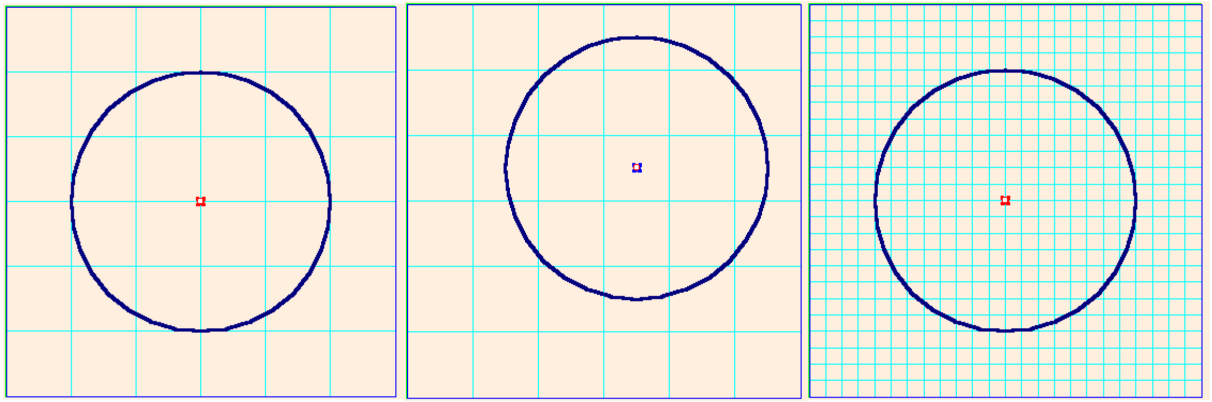
Conformal modelling of complex ovens & loads

Recalling pre-published results on local conformal approximations



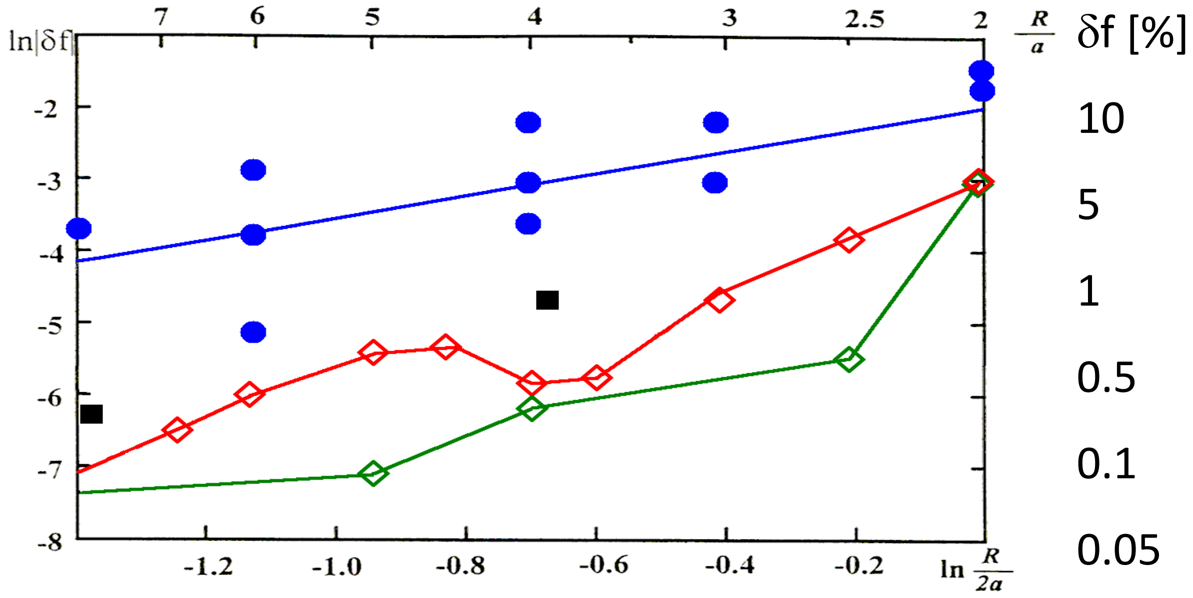
stair-case vs locally conformal mesh

coax line, hot-dog, donut



cross-section of: glass plate, pizza, cylindrical resonator

mesh 2..8 cells per radius; results depend on object location vs mesh



stair-case

no or simple merging (Railton & Schneider, *MTT Trans.* Jan1999)

directional cell merging

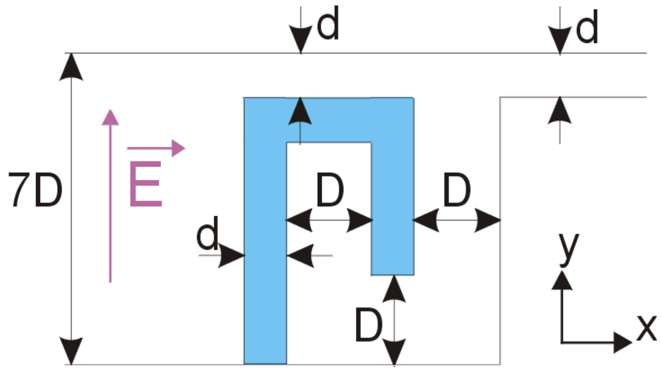
linearised directional cell merging

Conformal 2D FDTD as originally proposed by W.Gwarek, *IEEE Trans. MTT* 1985, 1988

Microwave Pioneer Award 2011

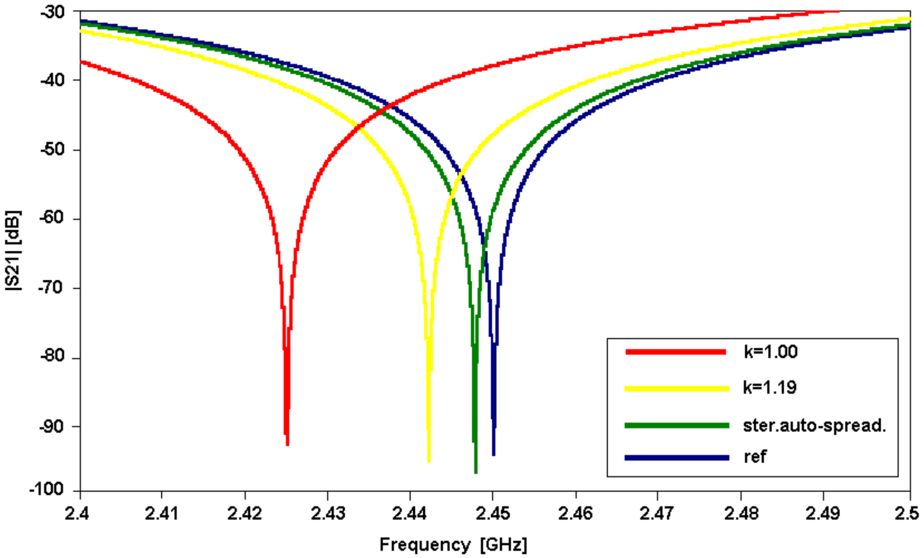
Modelling of field singularities at sharp metal edges

Recalling pre-published results on local conformal approximations

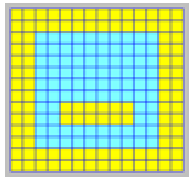


Choke of a MW oven in raw FDTD gives frequency error about 40x bigger than dispersion error.
Proper model suppresses singularity error to dispersion error.

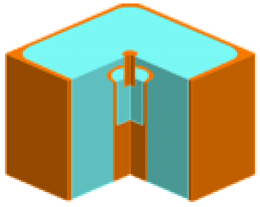
	errors by raw FD / FDTD	action by singularity models
E -field	ε ↑	ε ↓
H -field	μ ↓	μ ↑
Z_0	↓	↑
f	depends on mode	consider stability



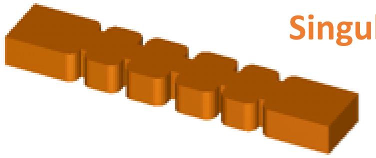
TEM transmission lines

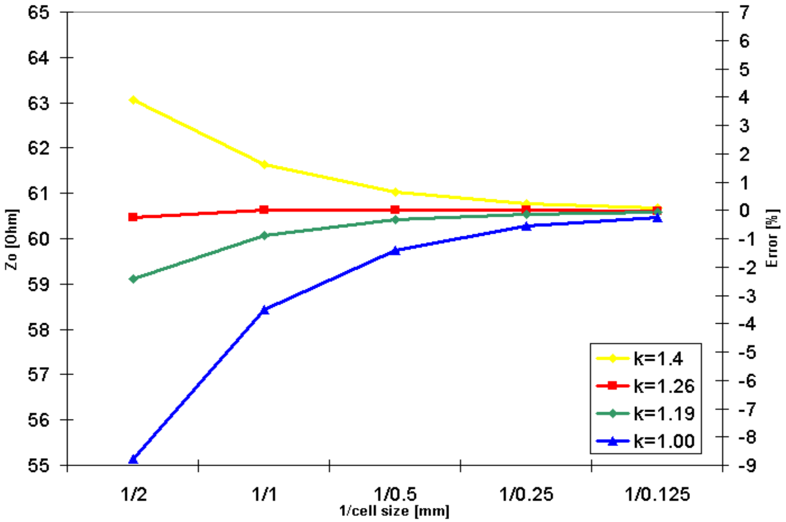


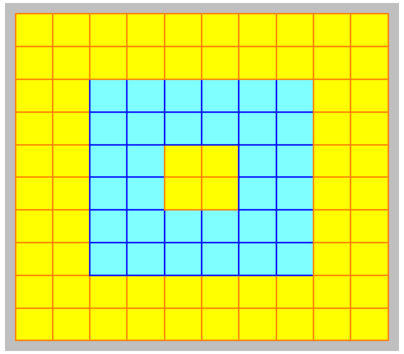
resonators



filters





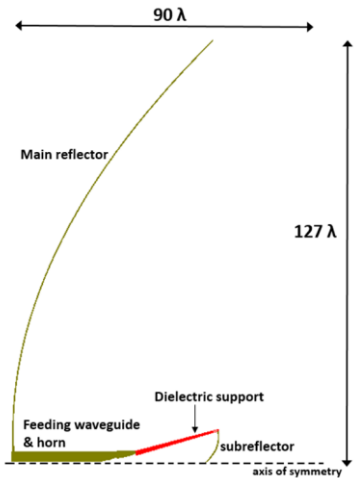


In TEM lines singularity errors of both field types boost the impedance error.
Singularity corrections become indispensable for analysis at computer effort.

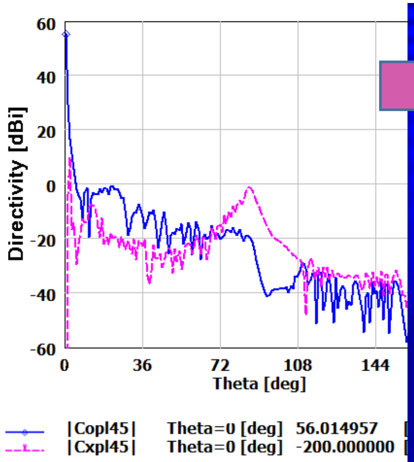
Stereoscopic singularity models
M.Celuch *IEEE IMS* 2003

Near-field insight into device performance

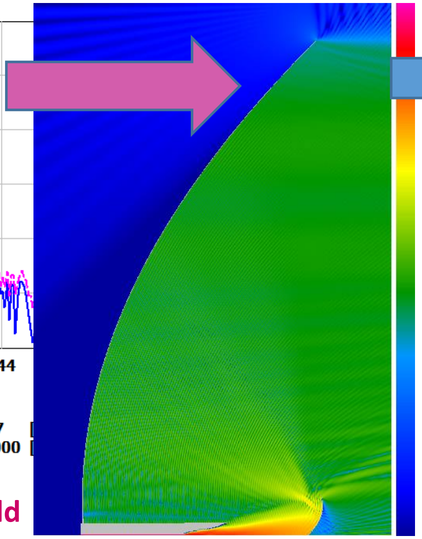
Unique, ultra-fast vector 2D Bessel & FDTD hybrid solver for design & analysis of devices with axial symmetry

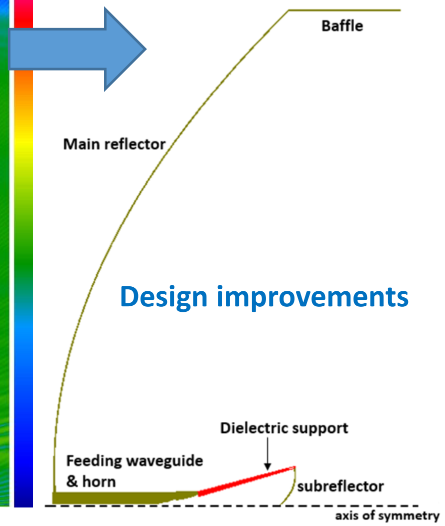


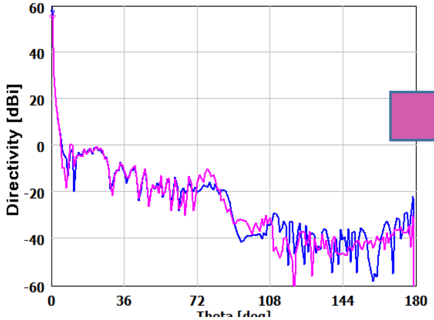
Dual -reflector antenna

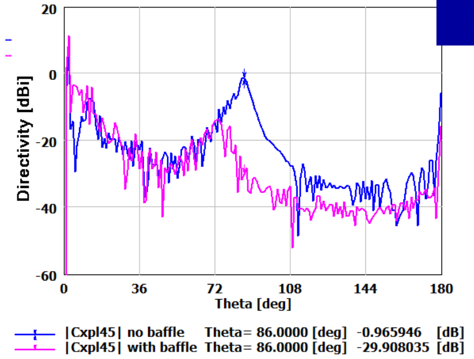


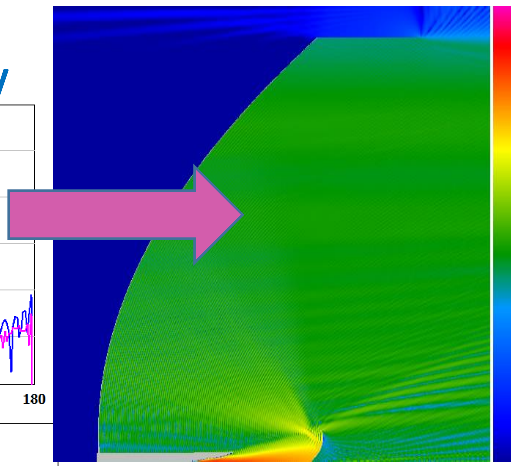
Insight into EM near-field





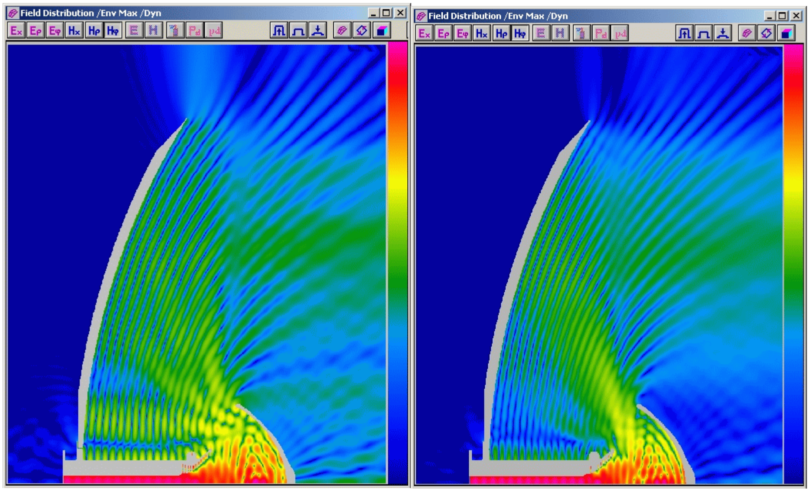






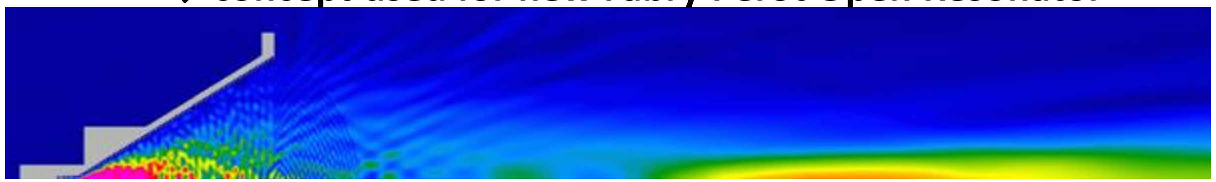
9m – diameter main reflector
Meshing: λ/40
Time to solution: 8 min
Radiation pattern @24 freq.,
Δθ=1deg : 5 s

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

Conclusions

- **Electromagnetic modelling is a powerful tool for the development of new material measurement methods:**
  - new test fixtures,
  - resolution improvement,
  - physical interpretation of the measured results.
- **Measurements are not "universal truth"; they are subject to definitions & conventions, just like the modelling.**
- **EM modelling in general-purpose software helps 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.**
- **Two approaches to commercial software development:**

- *black box* that quickly provides *solutions = numbers*,
- *virtual laboratory* that provides *physical insight*.

- **With this keynote I seek:**
  → advice on matrix inversion in imaging,
  → reseach collaborations to explore & enrich QuickWave modelling.

THANK YOU!