FDTD modeling of microwave power applicators

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Acknowledgements

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Program Badań Stosowanych

The **FDTD modeling** presented herein has been performed with multiphysics regimes of **QuickWave^{TM}** software by QWED, see:

- commercial & trial licences: https://qwed.eu/qw_trial.php
- Open Platform versions: https://qwed.eu/nanobat.html

Horizon 2020

The **microwave material characterization techniques** presented herein are being further developed within the European projects:

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Narodowe Centrum Badań i Rozwoju

Outline

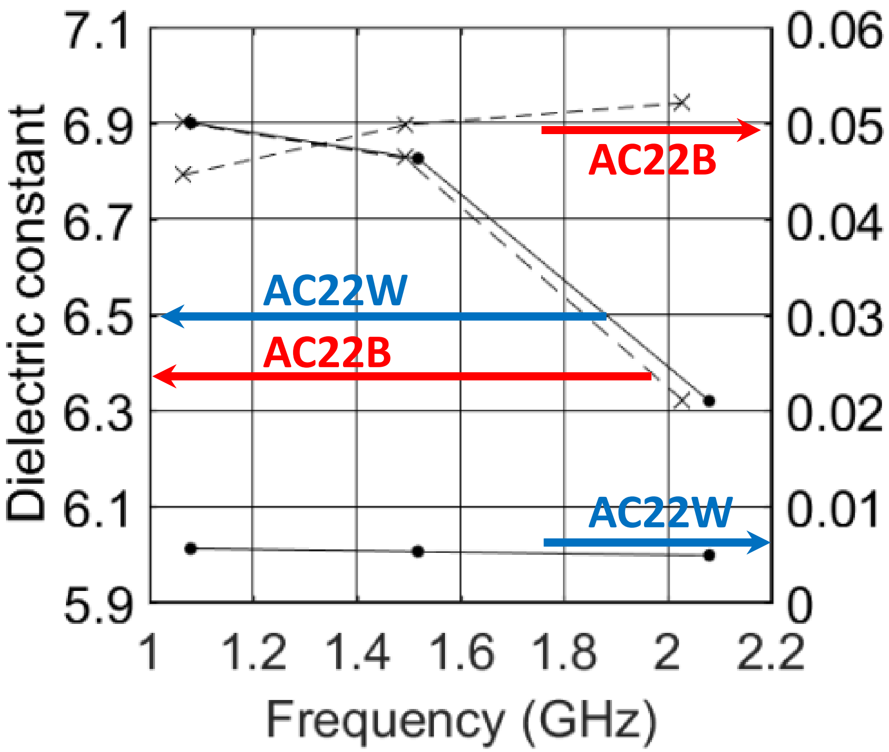
- Microwave treatment of asphalt pavements
- Microwave recycling of waste tires
- Conclusion

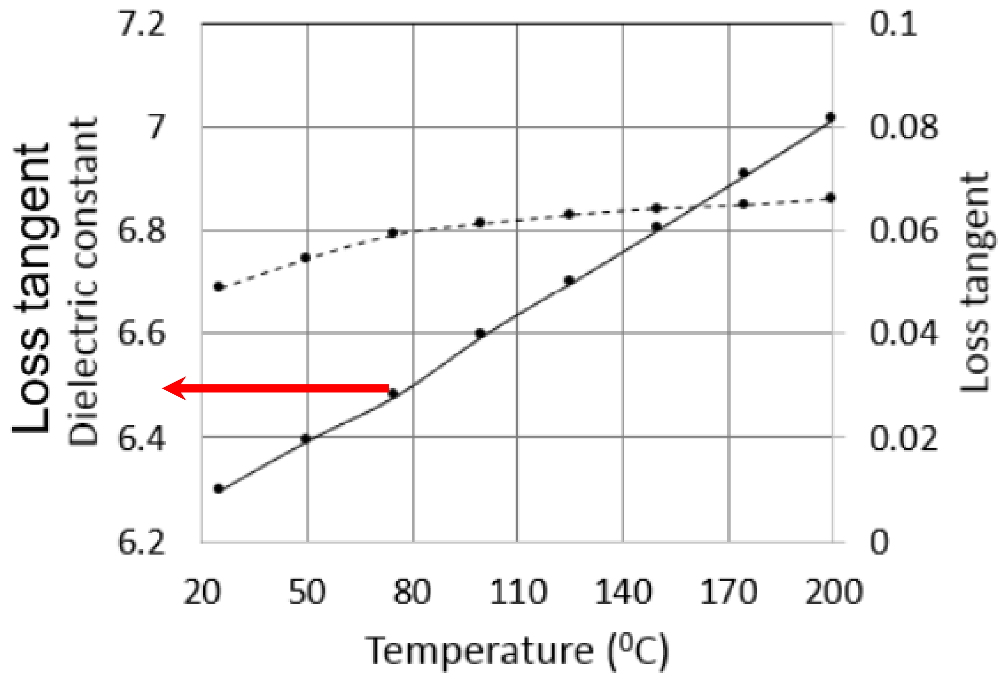
Asphalt pavements

- Longitudinal cracks in asphalt roads due to:
  - atmospheric conditions
  - road processing cycle
- Low effectiveness and repeatability of typical thermal bonding process

Materials

Measurements undertaken with cavity resonators.





AC22B

AC22B – asphalt with basalt aggregates

AC22W – asphalt with limestone aggregates

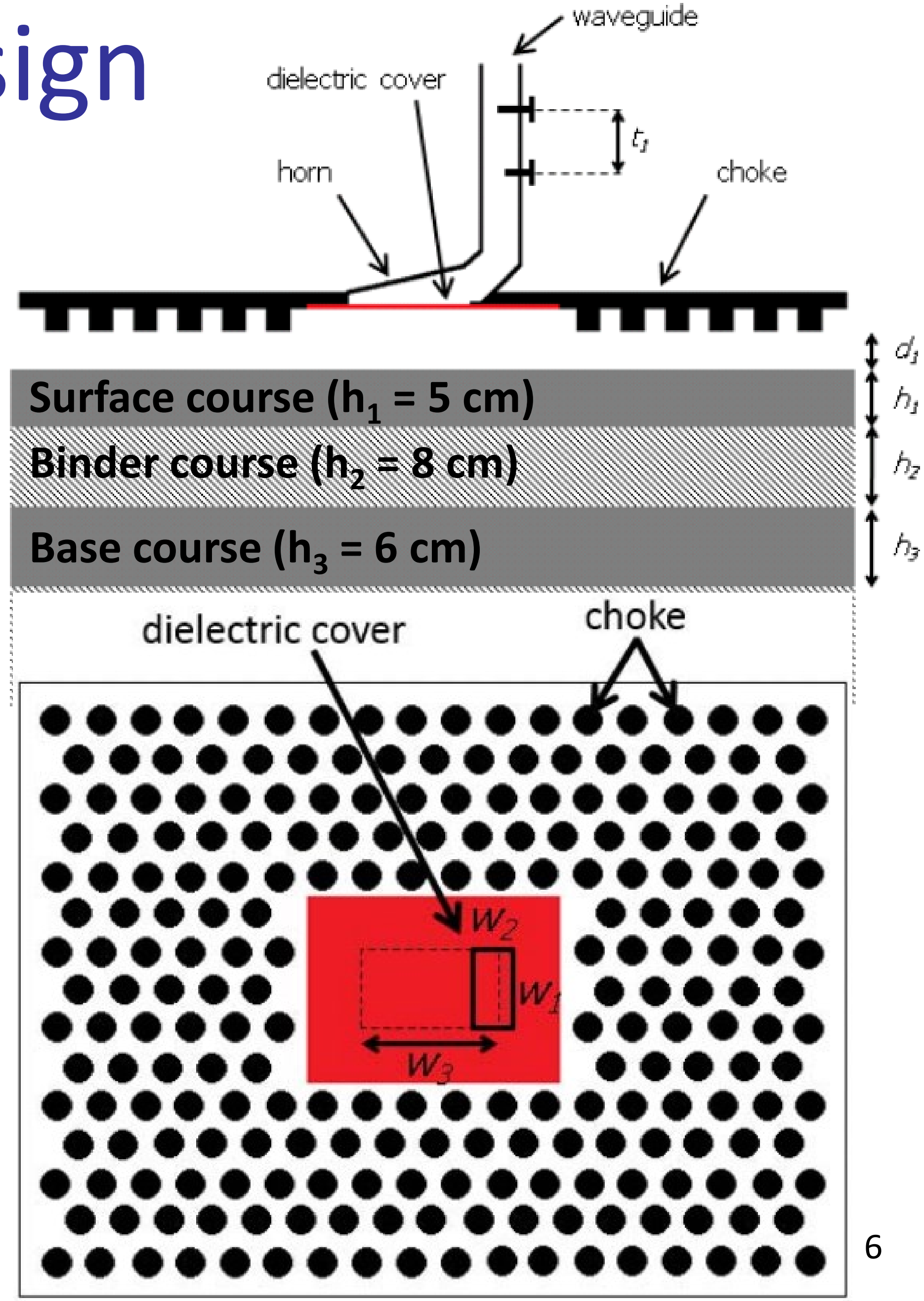
Asphalt binder: ε_r = 2.65, tanδ = 0.00163 @ 2.45GHz

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

Design

- WR-340 waveguide with an oblique horn (for impedance matching)
- Polycarbonate cover

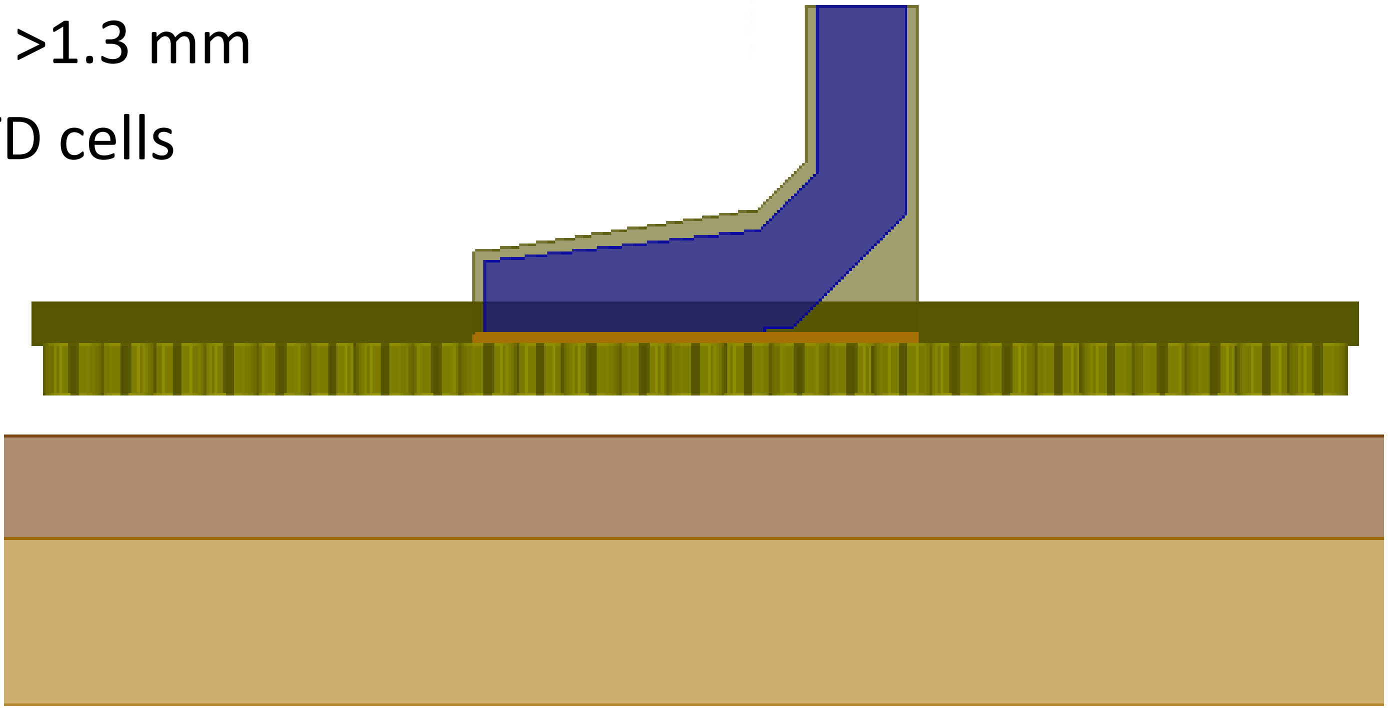
  (ε_r = 2.8, tanδ = 0.00554 @ 3GHz)
- 2-stub tuner
- Choke with cylindrical stubs in a hexagonal lattice
- 3-layer road model



Parameter	Basaltic aggregate	Limestone aggregate
Surface course (ε_{r1} /tanδ_1)	6.5 / 0.052	6.3 / 0.0049
Binder course (ε_{r2} /tanδ_2)	6.5 / 0.026	6.3 / 0.0024
Base course (ε_{r3} /tanδ_3)	6.5 / 0.0	6.3 / 0.0

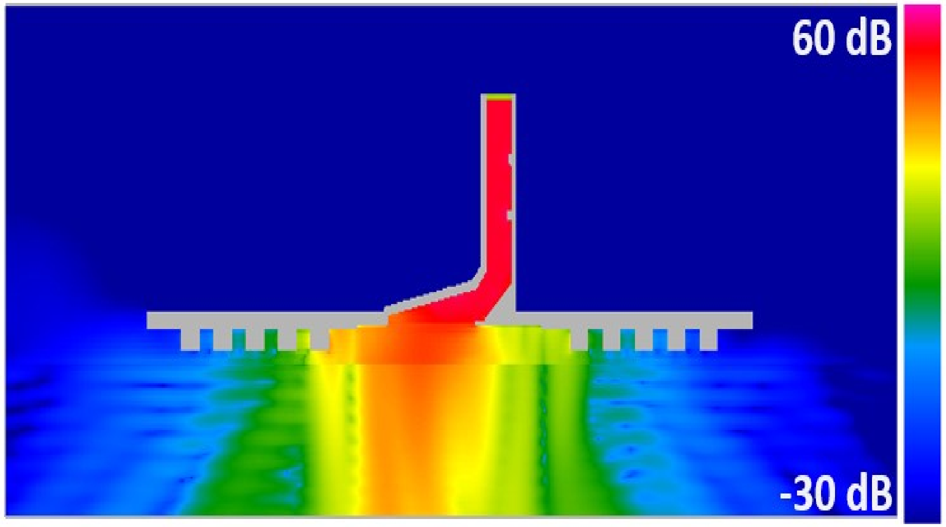
FDTD model

- Performed with FDTD (QuickWave-3D)
- FDTD cell size: >1.3 mm
- 9.4 milion FDTD cells
- 779 MB RAM
- 26 seconds

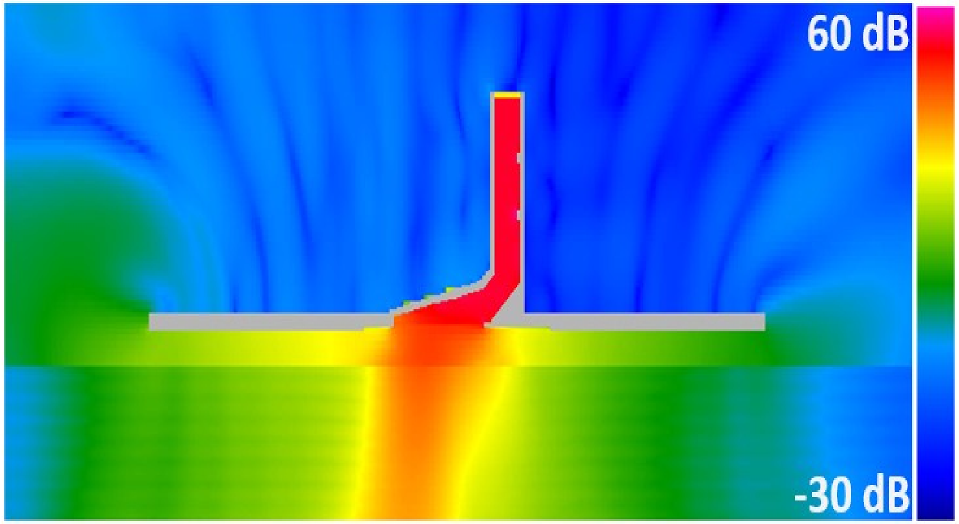


EM fields

- 50% of delivered power is dissipated in 3 asphalt layers
- … 31% in the surface course
- … $\eta = 13.5\%$ directly under the horn
- Shielding effectiveness of chokes: >40 dB
- P_{rad}= 1.5 W for P_{in}= 30 kW
- 120 mW/m² at 1m distance



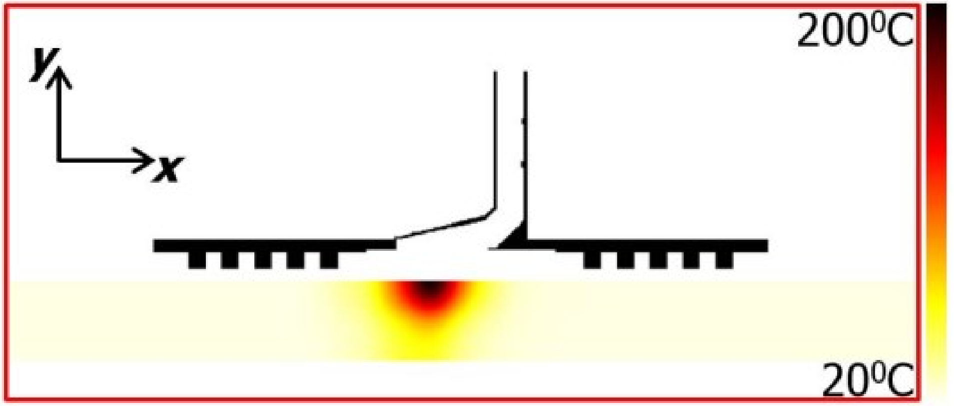
With chokes



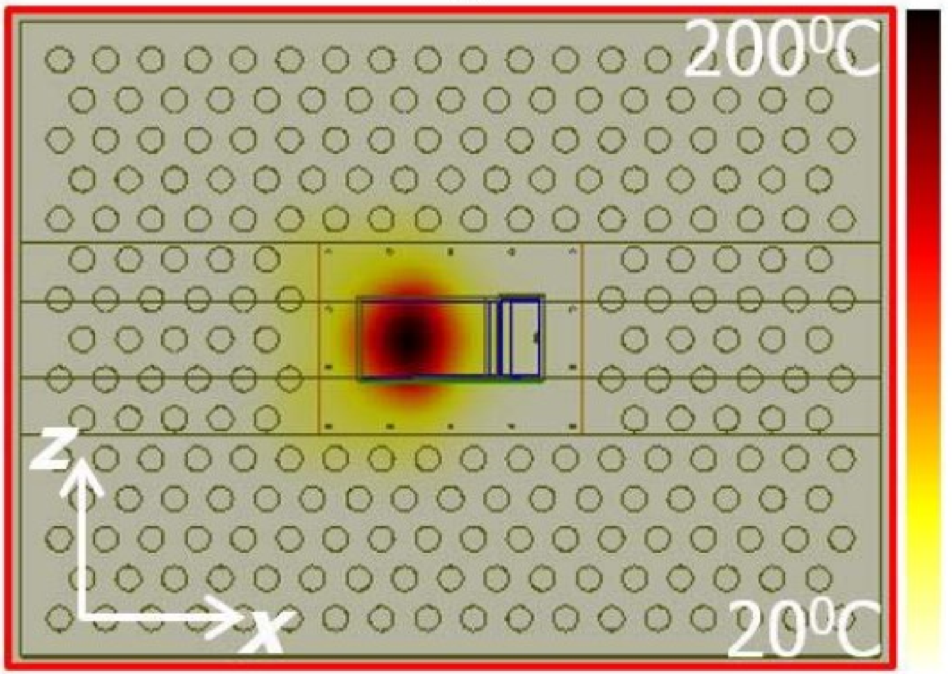
Without chokes

Thermal simulation

- Performed with FDTD (QuickWave-BHM)
- 15 minutes of heating with 1kW of mean available power
- Heating area: 60 x 70 cm^2 = = 0.42 m^2
- Linear increase of temperature up to 196 ^{0}C
- Heating rate: $4.75\,°C/min$ for basaltic aggregates

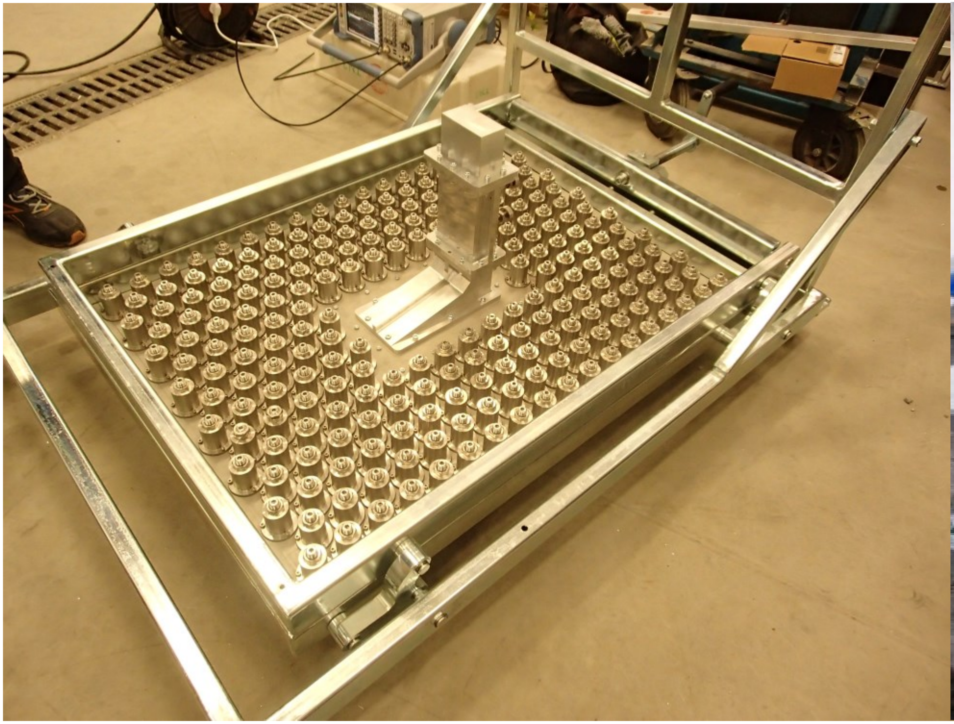
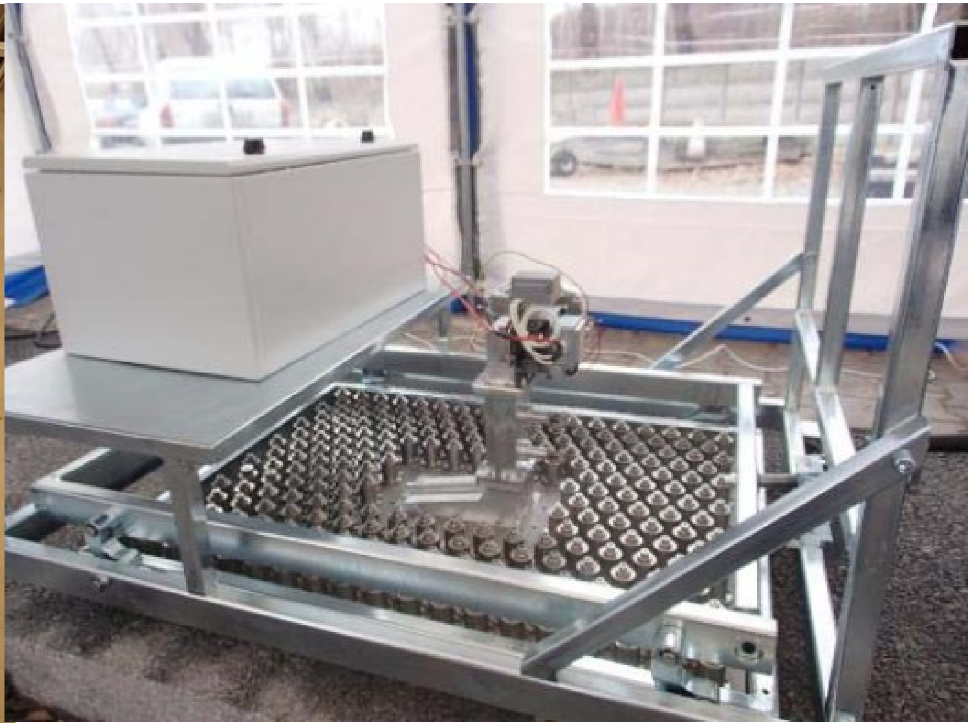


(a)



(b)

Prototype

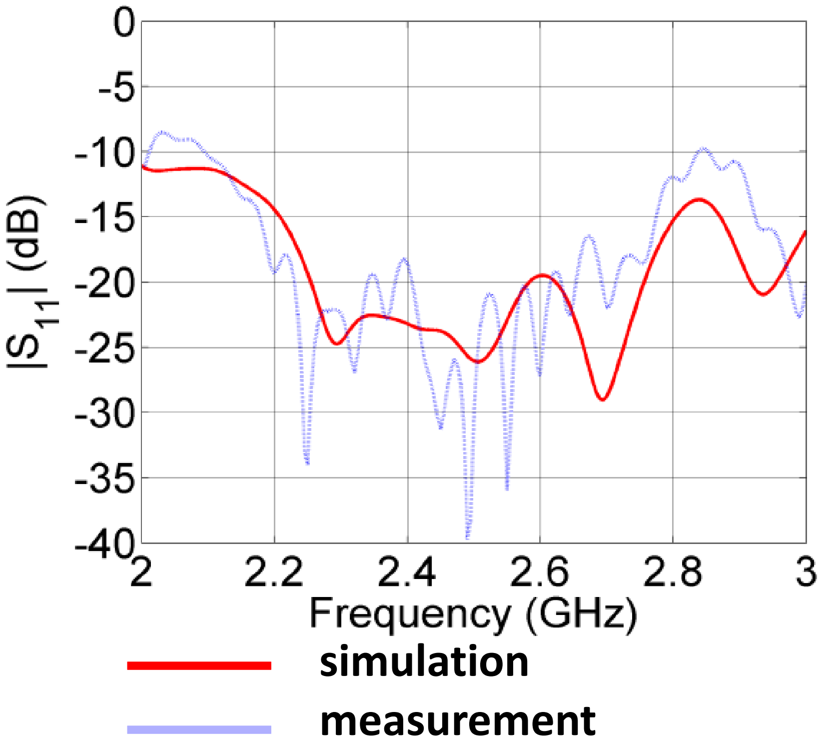



Portable applicator developed for tests on site

with one waveguide horn

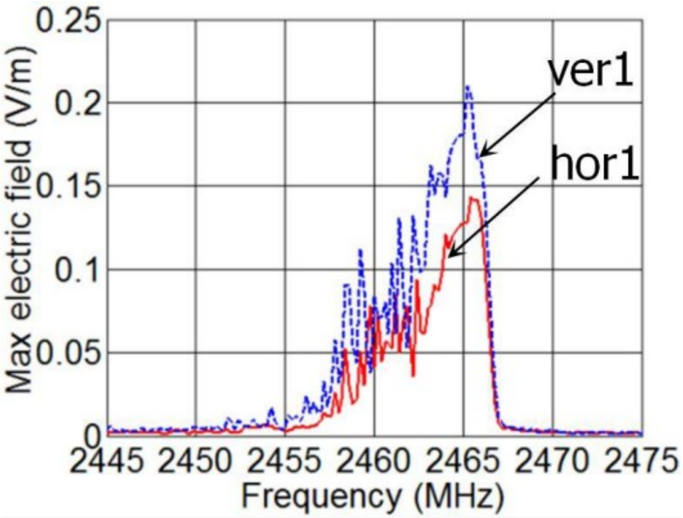
Impedance matching

- 1kW magnetron 2M244-M16 (2.46 ± 0.01GHz)
- $|S_{11}|$< -23dB in magnetron's operating range
- Ripples are due to 1.5m-long cables

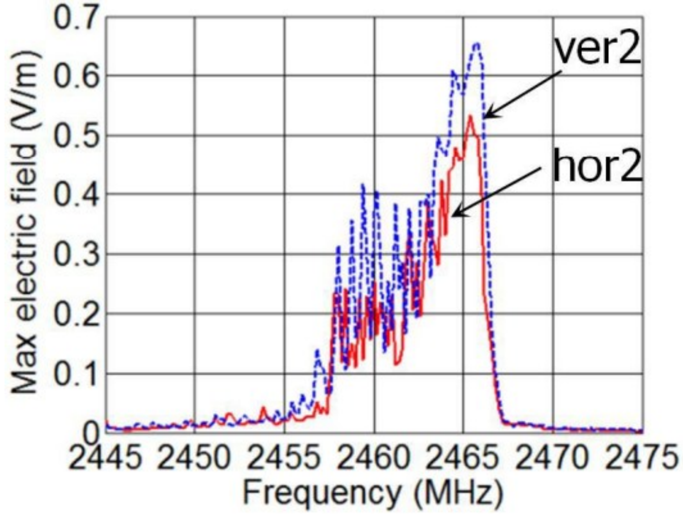


Exposure levels

- 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

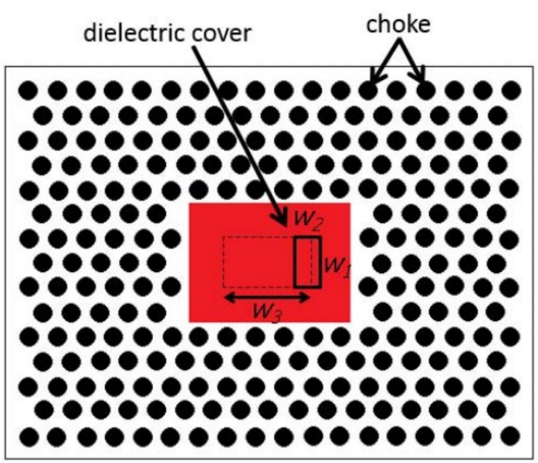


Front exposure



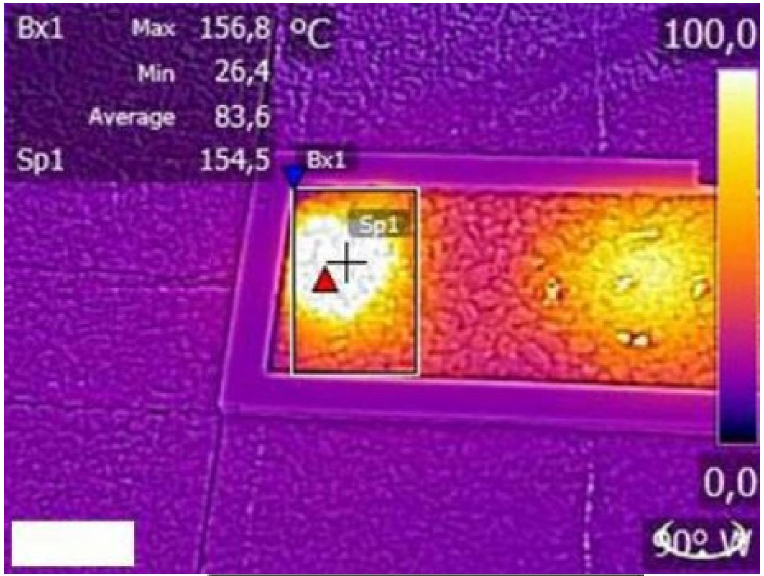
Side exposure

Front



Side

Thermal signatures



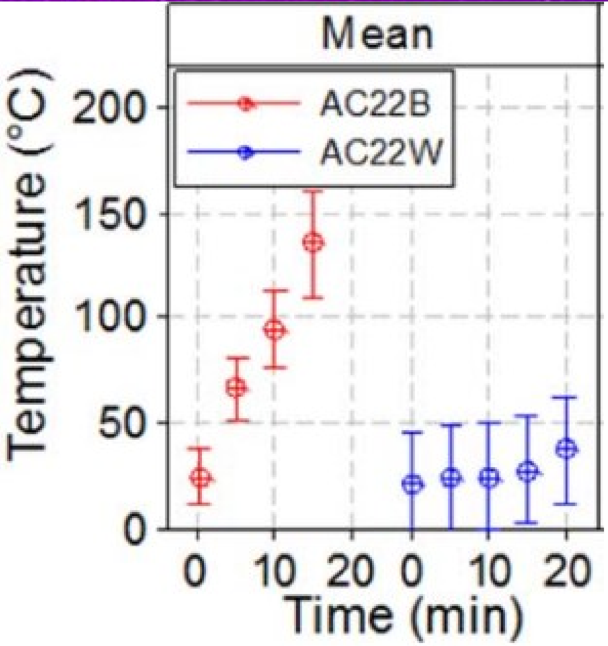
1. Max heating rates:

AC22B – 16.4 ^{0}C/min

AC22W – 0.8 ^{0}C/min

2. Increase of power from 1kW up to 14.25kW for AC22W would have made the heating rates equal.

3. Good agreement with FDTD (AC22B)



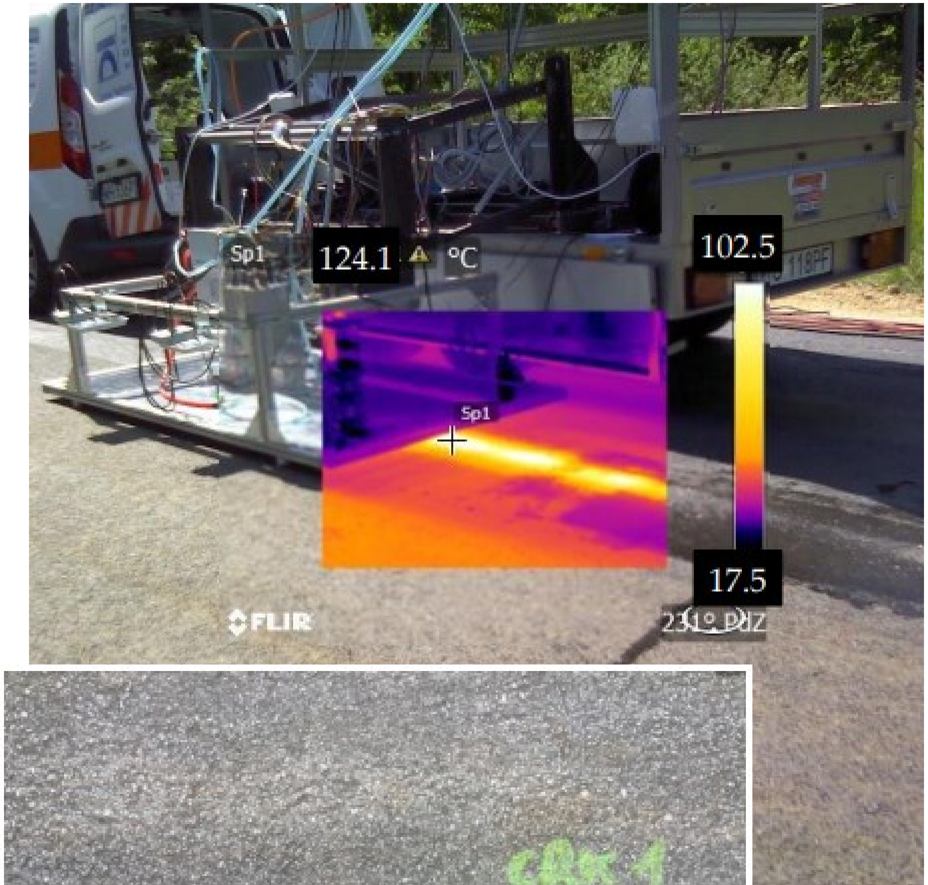
AC22B – asphalt with basalt aggregates
AC22W – asphalt with limestone aggregates

On site testing

Heating speed (P_{in} = 7 kW, ΔT = 100 °C):

AC22B – 1 meter/min

AC22W – 0.1 meter/min



Before exposure

After exposure

Conclusion

- Microwave treatment of asphalt pavements has to be calibrated to a given type of aggregates (basalt vs. limestone)
- Heating rate: 16.4 ^{0}C/min/kW for basalt and 0.8 ^{0}C/min/kW for limestone
- Exposure to high-power MW radiation bonds asphalt cracks across the whole thickness of the pavement

Waste tires

- Goal: tire devulcanization
  (recycling of rubber, carbon, sulphur and other compounds)
- Estimation: 1-2 billion tires disposed every year
- Expected throughput: 200 kg/h
- Source type: low-cost magnetrons

www.recyclechina.com

www.cleveland.com

Power budget – heating stage

TABLE I

CAR TIRE COMPOSITION

	CB	NR	SR	S
Vol. fraction, v_f, %	28.0 (35.4)	14.0 (17.7)	27.0 (34.2)	10.0 (12.7)
Density, ρ, g/cm^3	12	0.91	1.5	7.5
Spec. heat, C, J/g/K	0.7	2.0	2.0	0.49

CB – carbon black, **NR** – natural rubber, **SR** – synthetic rubber, **S** - sulphur

if other components are neglected

Input data

throughput = 200 kg/h

temperature rise: 400 – 20 = 380 ^{0}C

volume fraction of scrap tires: v_f = 30%

$\boldsymbol{P_h = 20.9kW}$ of microwave power is needed to heat a 2.5 x 1.0 x 0.3 m^3 volume of scrap tires by 380 ^{0}C during 26 minutes of microwave processing

Power budget – dissociation stage

Input data

- Dissociation temperature of sulphur-sulphur and carbon-sulphur bonds: 400 ^{0}C
- Sulphur mass content is assumed to m_s = 2.5%
- The same amount of S-S and C-S bonds

$$\boldsymbol{P_d = 15.4kW}$$

of microwave power is needed to dissociate all S-S and C-S bonds at 400 ^{0}C

$$\boldsymbol{P_t = \frac{(P_h + Pd)}{70\%} = \frac{36.3\ kW}{70\%} = 51.8\ kW}$$

total microwave power consumption (if 70% efficiency is achieved)

Cavity spec

Input data

- modular build of an applicator to make the system extendable

  (width: 1.0m, height: 0.3m, length: 2.5m)

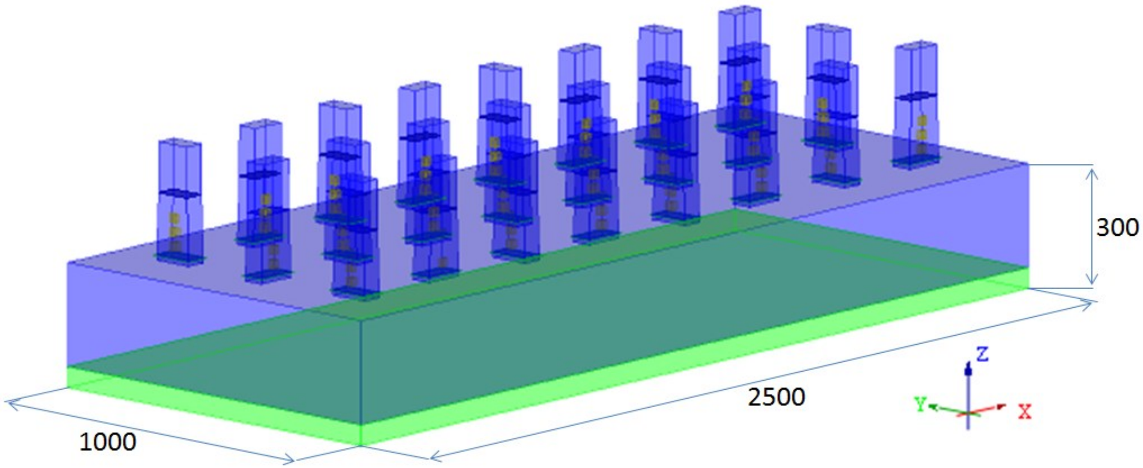
- stainless-steel conveyor belt with the load supplied via special oil containers
- cavity made of a low-carbon stainless steel (1.05×10^6 S/m)
- gas discharging pipes at the side walls (suppress MW leakage)
- tires cut into ca. 100mm scraps and evenly spread on the belt
- no leakage chokes due to external gaseous chamber

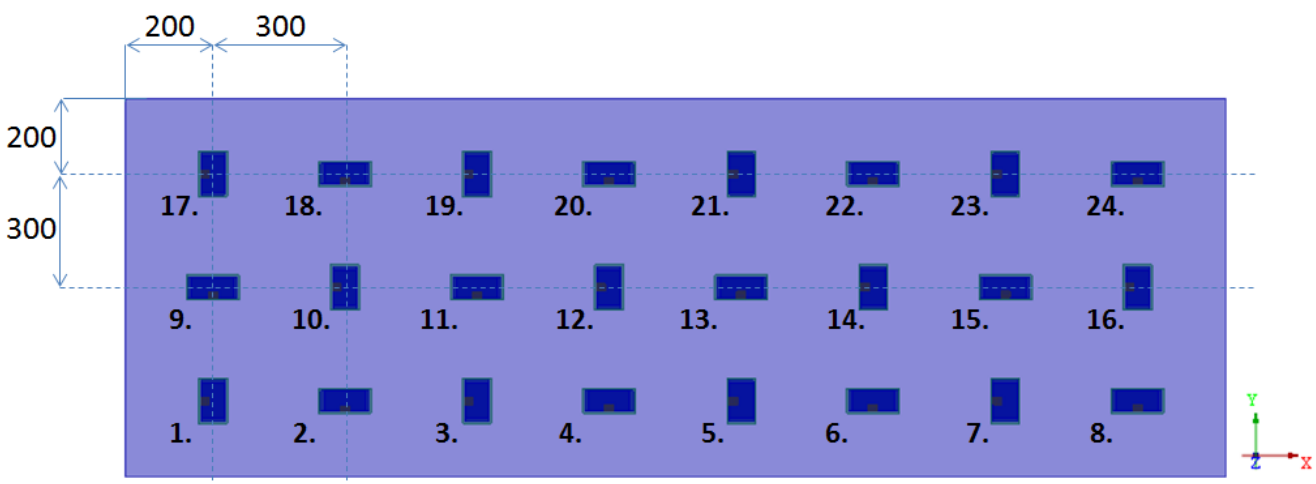
Cavity model

Alternate orientation of consecutive waveguides increases isolation between neighboring sources.

3 rows

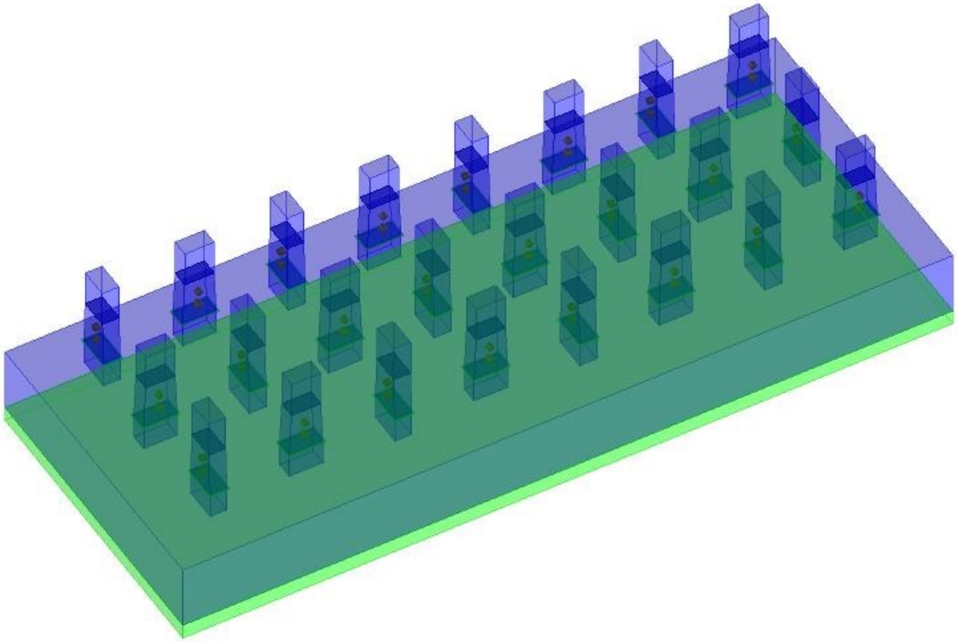
8 columns

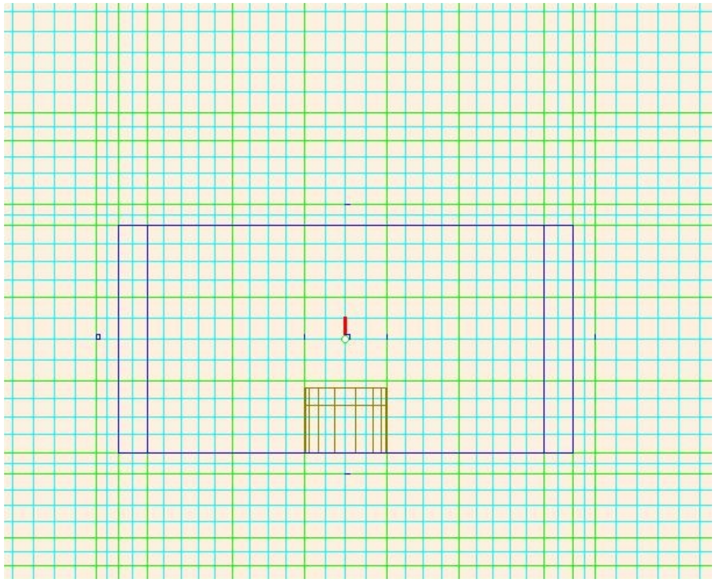




EM model

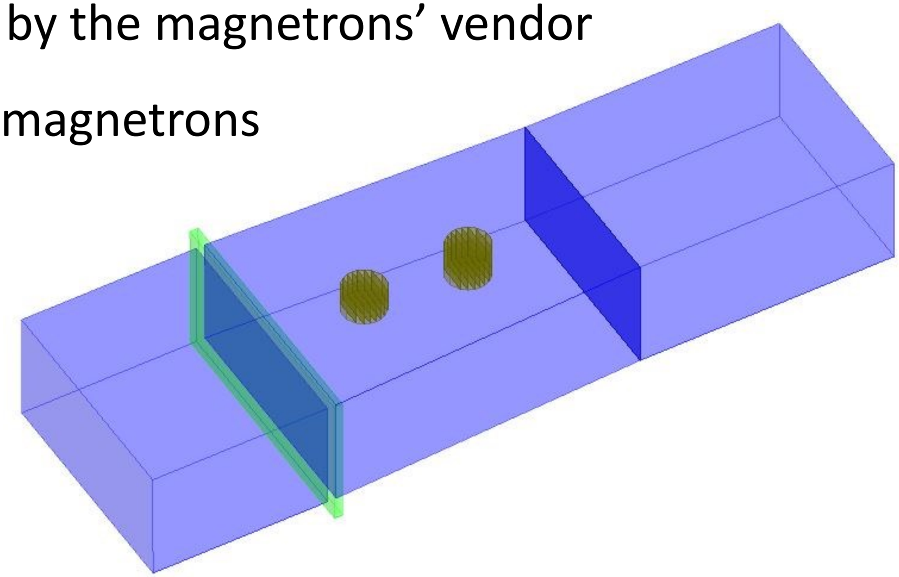
- The size of a model: 16 million FDTD cells
- Minimum cell size: *a* = 2mm (35-60 cells/λ)
- Simulation time: ca. 1 minute
- Waveguide sources per section: 24

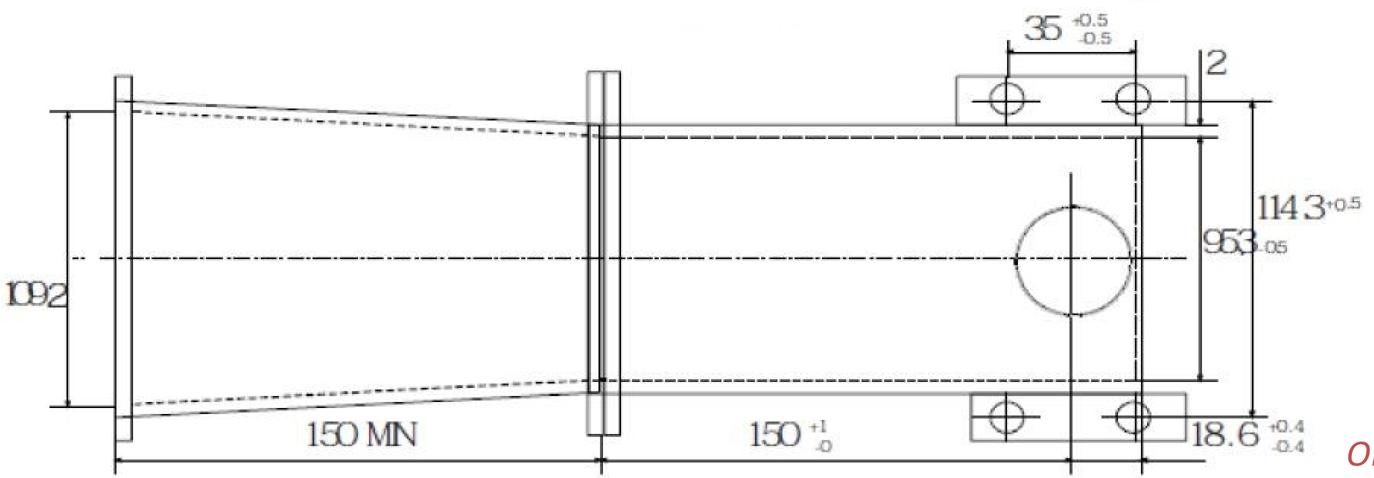




Feeding waveguides

- Waveguide launchers – as recommended by the magnetrons' vendor
- Alumina plates (99.5% Al_2O_3) to separate magnetrons from a gaseous section
- Two adjustable screws ($\phi = 20$mm) for waveguide tuning
- Tuning in cold conditions



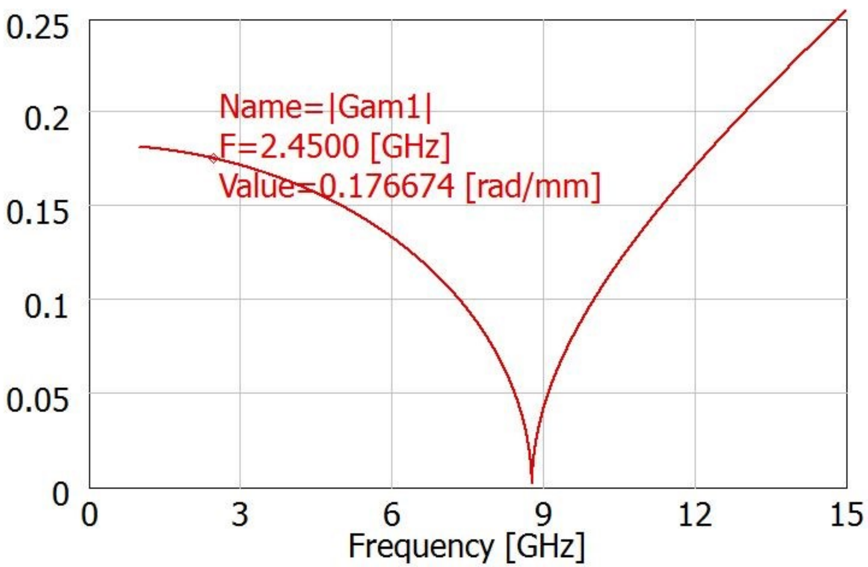


OM75P technical specification

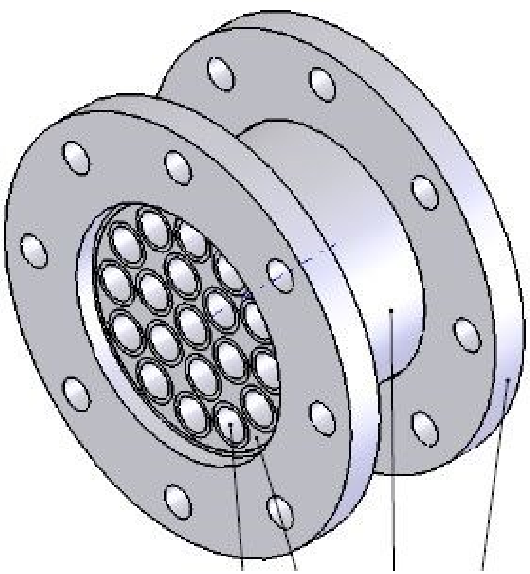
Discharging pipes

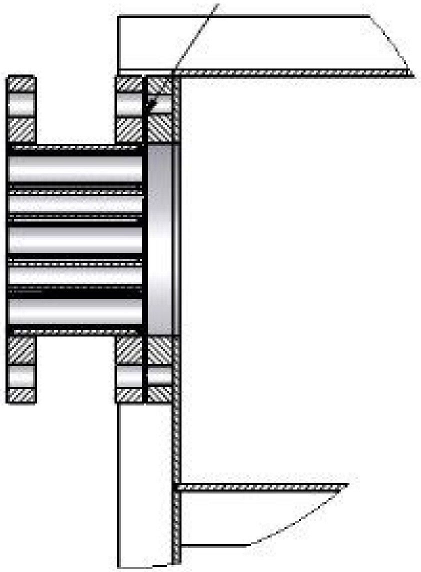
- The bunch of pipes discharging produced gases

  mounted in several locations along the cavity
- Pipes are *L* = 100 mm long to suppress EM leakage (evanescent mode)



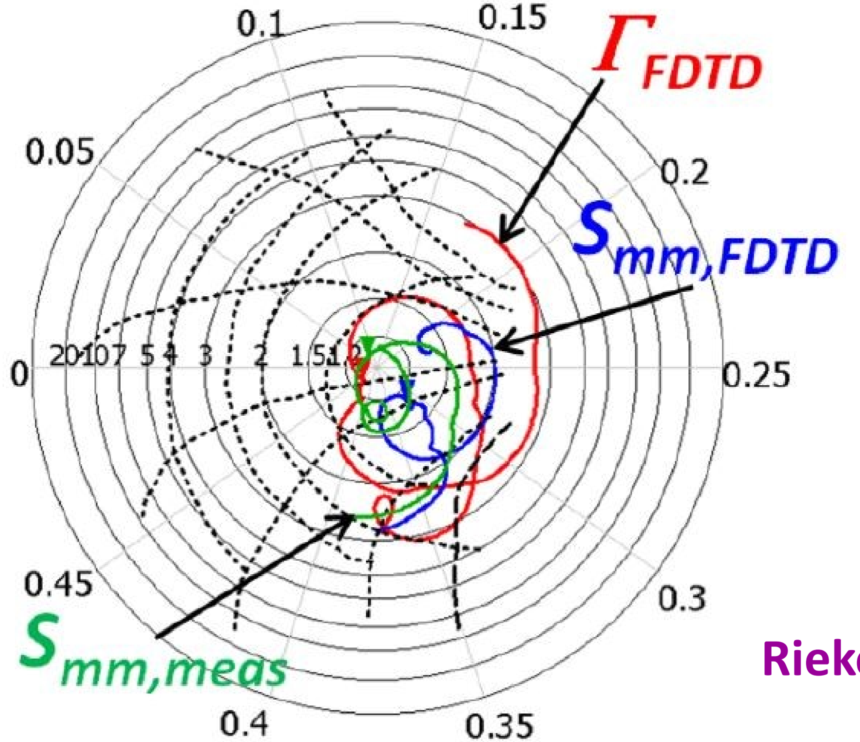
$$|S_{21}| = e^{-\alpha L} \Rightarrow -153\ \mathrm{dB}$$





Power balance

- [S] parameters are not appropriate measure of power balance in a multi-source network
- Instead, Γ should be measured at each source (with all the sources operating simultaneously)



Rieke diagram

Tests

- 24 waveguides in each of 3 conveyor sections
- Temperature: 380 ^{0}C (assumed: 380 ^{0}C)
- Throughput: 150 kg/h (computed: 200 kg/h)
- Outcome: solid carbon pieces, oil ingredients

Conclusion

- Microwave devulcanization of car tires can be one of energy-efficient recycling solutions
- Efficiency of 3 kg/h/kW has been achieved
- The outcome is: carbon and sulphur

Thank you for the attention!

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