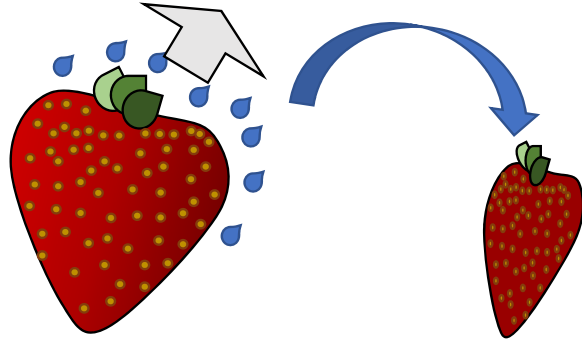

Microwave assisted vacuum drying processing:
magnetron vs solid state.
Case study: apple drying

Presenter: C. Bianchi (M. Eng., PhD)

Authors: C. Bianchi, R. Schmid, D. Frick

Department: Research & Development

Company: Gigatherm Mikrowellen AG

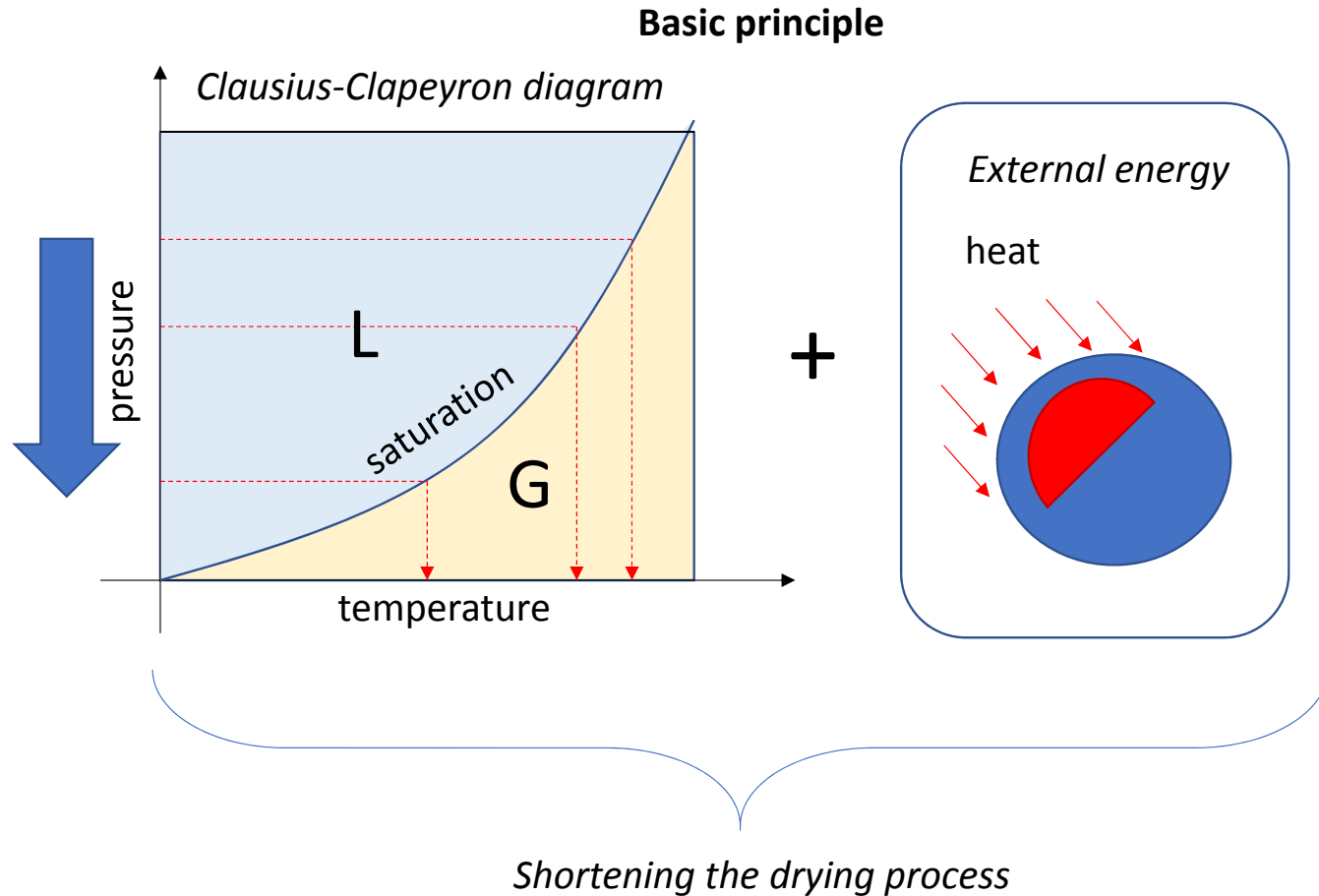


Advantages

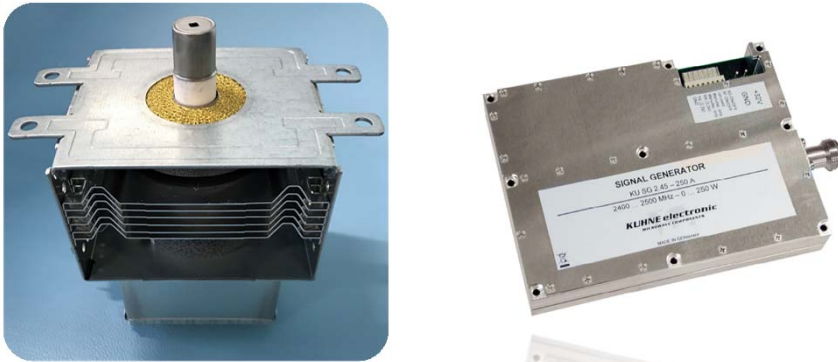
- Inhibition of microbial growth
- Extended shelf life of food
- Less weight (transportation)
- Maintaining sensorics quality and flavour profile

Challenges

- Shortening the process duration
- Reaching a very gentle process
- Temperature should be kept low



Vacuum drying: why Microwaves?



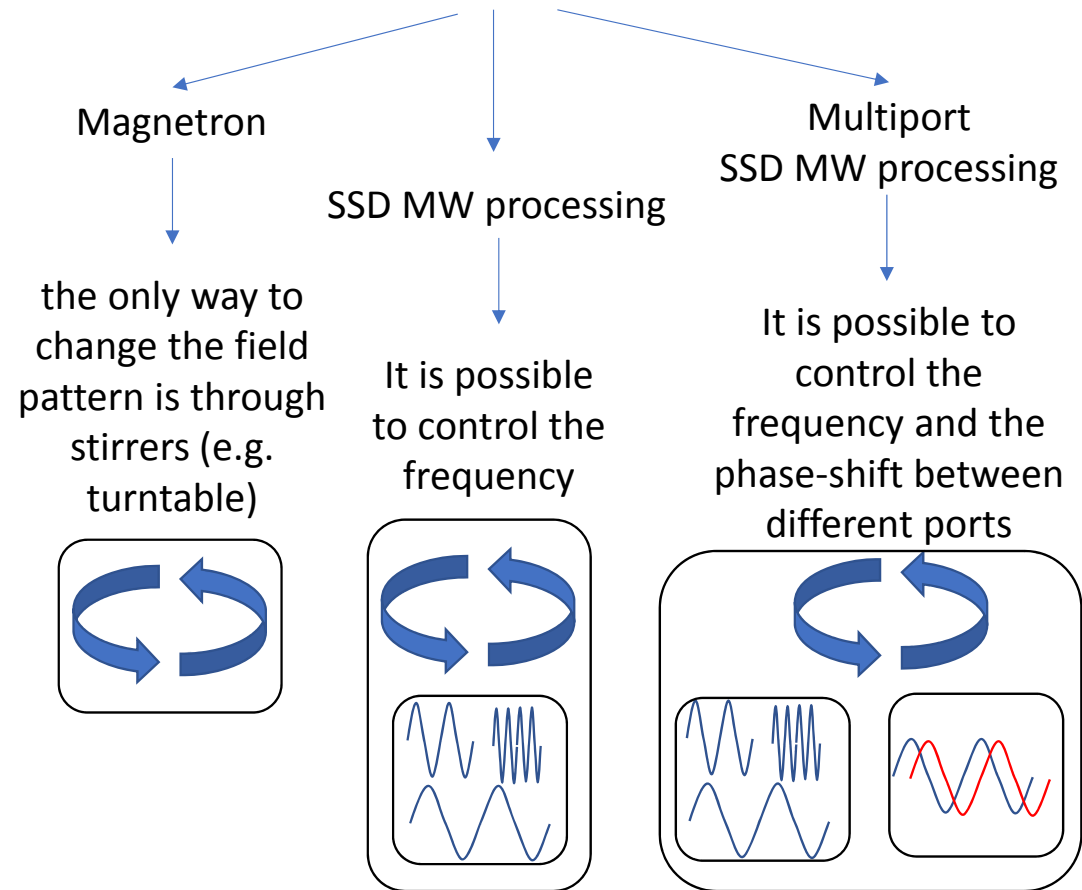
Dielectric volumetric heating

- Energy is directly converted within the material (efficiency)
- Water contained in the product is the main responsible for MW absorption (selectivity)
- Energy transfer rate is not related to temperature gradient

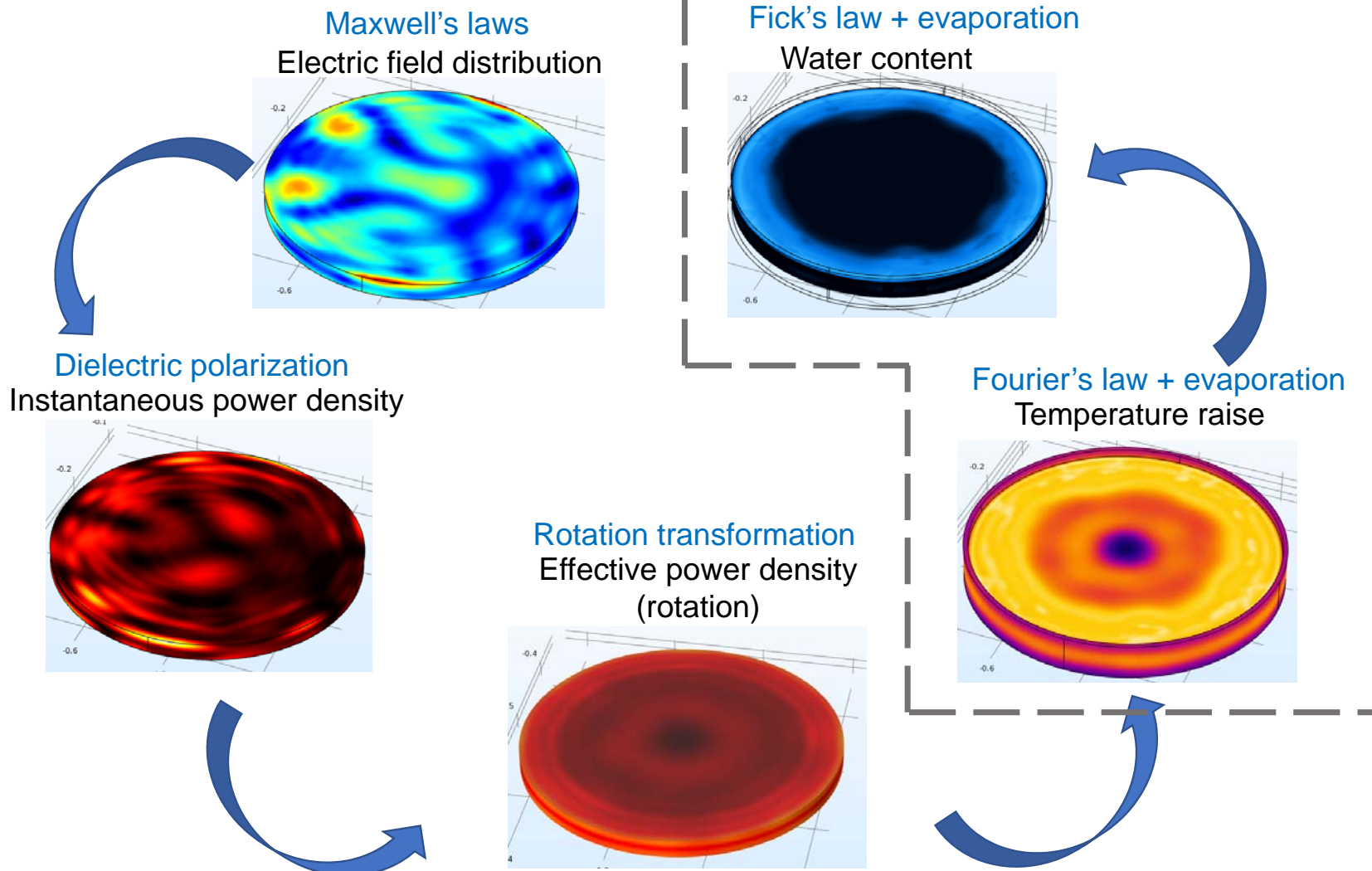
Challenges

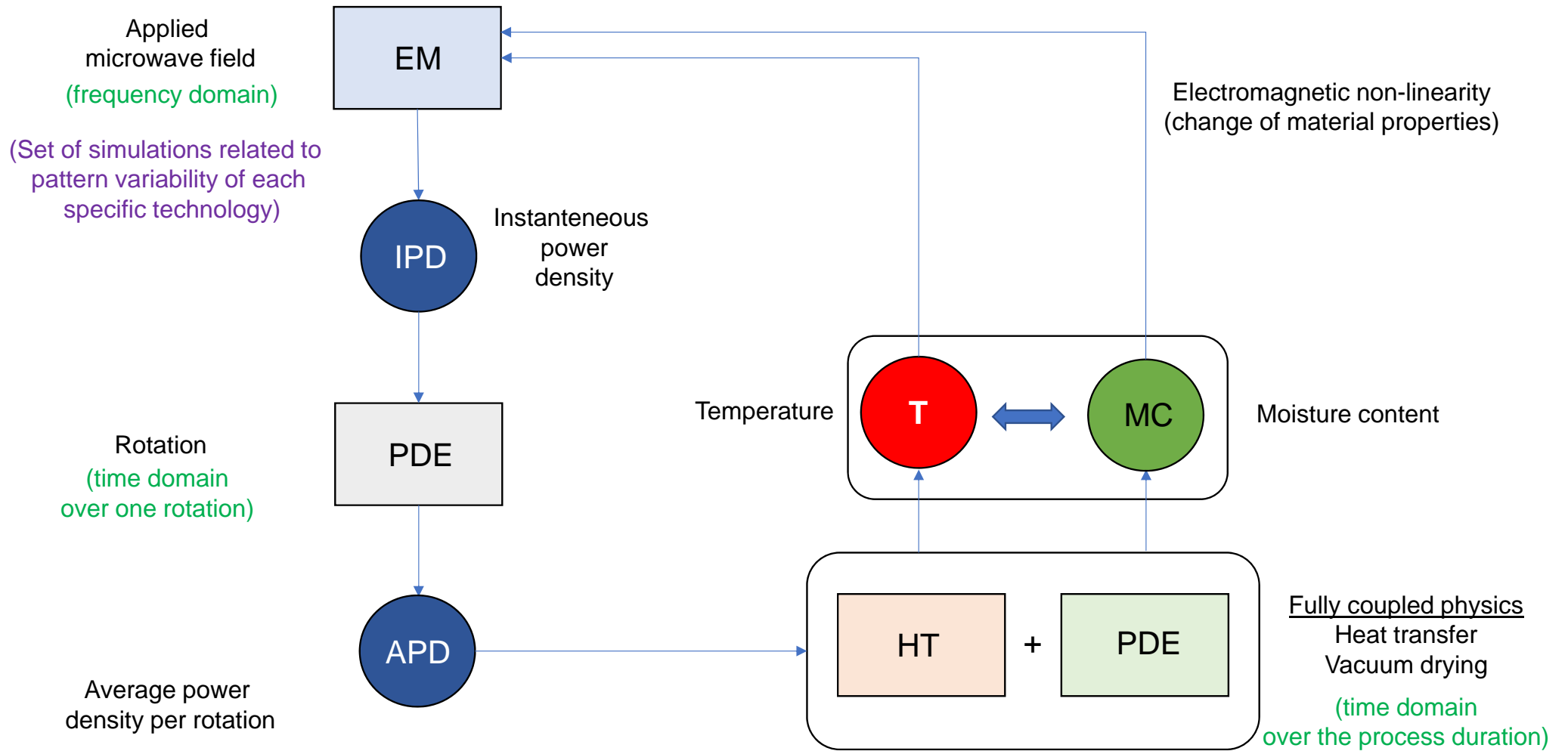
- Achieving a very homogeneous process despite the presence of EM standing waves

Comparing different MW technologies



Vacuum Drying of Food: physical steps





Boundary conditions

RF Electromagnetics

$$\mathbf{n} \times \mathbf{E} = \mathbf{0} \quad \text{Perfect Electric Conductor}$$

$$S = \frac{\int_{\partial\Omega} (\mathbf{E} - \mathbf{E}_1) \cdot \mathbf{E}_1}{\int_{\partial\Omega} \mathbf{E}_1 \cdot \mathbf{E}_1}; \quad TE_{10} \text{ EM propagation mode}$$

Heat transfer

$$\mathbf{q} = h(T_{ext} - T) \quad \text{Low level natural convection}$$

Vacuum drying

$$\mathbf{n} \cdot c\Delta\theta_L = 0 \quad \text{No flux of } \theta_L$$

B.C. is already included as mass depletion due to evaporation (sink term).

Initial conditions

RF Electromagnetics

$$\mathbf{E}(x, y, z) = \mathbf{0} \quad \text{Absence of field}$$

Heat transfer

$$T(x, y, z) = 20^\circ\text{C} \quad \text{Environmental temperature}$$

Vacuum drying

$$\theta_L(x, y, z) = 0.84 \quad \text{Fresh product water content}$$

These conditions are necessary to compute the numerical solution of the PDE equations which are associated to each physics, and to guarantee uniqueness of results.

RF Electromagnetics

$$\nabla \times \mu_r^{-1}(\nabla \times \mathbf{E}) - k_0 \left(\epsilon_r - \frac{j\sigma}{\omega\epsilon_0} \right) = 0$$

Electric field

\mathbf{E}

Static power density

$$spd(x, y, z) = 2\pi f \epsilon_0 \epsilon_r'' |\mathbf{E}|^2$$

Rotation of power density

$$ipd(x, y, z, t) = \sum_i spd_i(x + X_r - X_g, y, z + Z_r - Z_g) \cdot pw_{a1}(prob(t))$$

Average power density

$$apd(x, y, z) = f_{rot} \int_0^{1/f_{rot}} ipd(x, y, z, t) dt$$

Rotation of the turntable

Step function

Random number function over time

$$X_r = (X_g - X_0) \cdot \cos(2\pi f_{rot} t) - (Z_g - Z_0) \cdot \sin(2\pi f_{rot} t) + X_0$$

$$Z_r = (X_g - X_0) \cdot \sin(2\pi f_{rot} t) - (Z_g - Z_0) \cdot \cos(2\pi f_{rot} t) + Z_0$$

Heat transfer

$$\rho c_p \frac{\partial T}{\partial t} + \rho c_p \cdot \nabla T + \nabla \cdot \mathbf{q} = Q$$

$$\mathbf{q} = -k_{th} \nabla T$$

Vacuum drying

$$\frac{\partial \theta_l}{\partial t} + \nabla \cdot (-c \nabla \theta_l) = - \frac{\dot{m}}{\rho_{water}}$$

$$\dot{m} = k_{vap} \cdot \rho_{wat} \left(\frac{P_{sat}(T) - P_{ch}}{P_{ch}} \right)$$

Temperature and moisture

T
 θ_l

Material phases of the food product

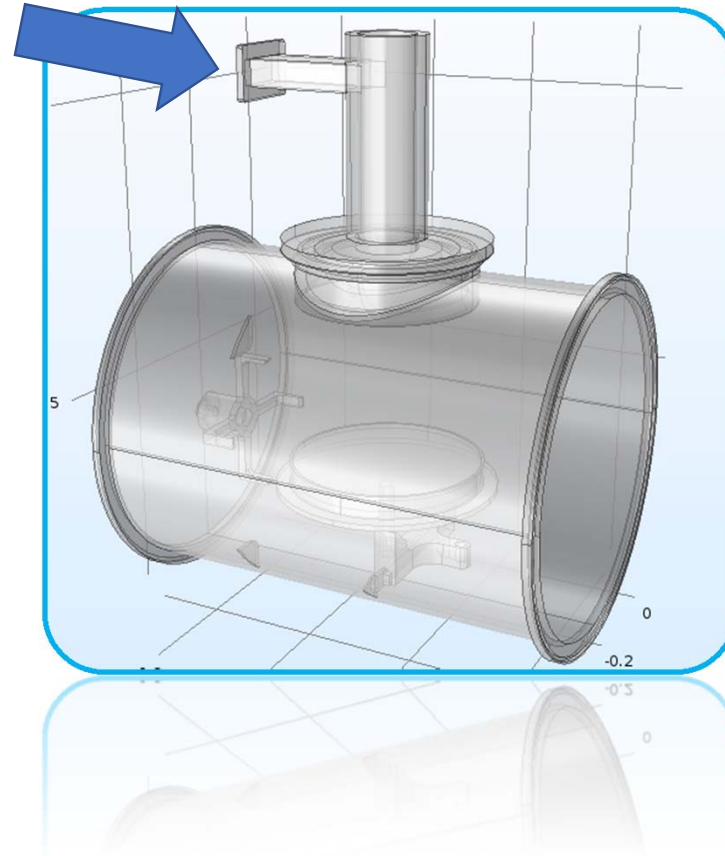
$$\theta_g = 1 - \theta_l - \theta_s$$

$$c_p = f(\theta_l) \quad k_{th} = f(\theta_l)$$

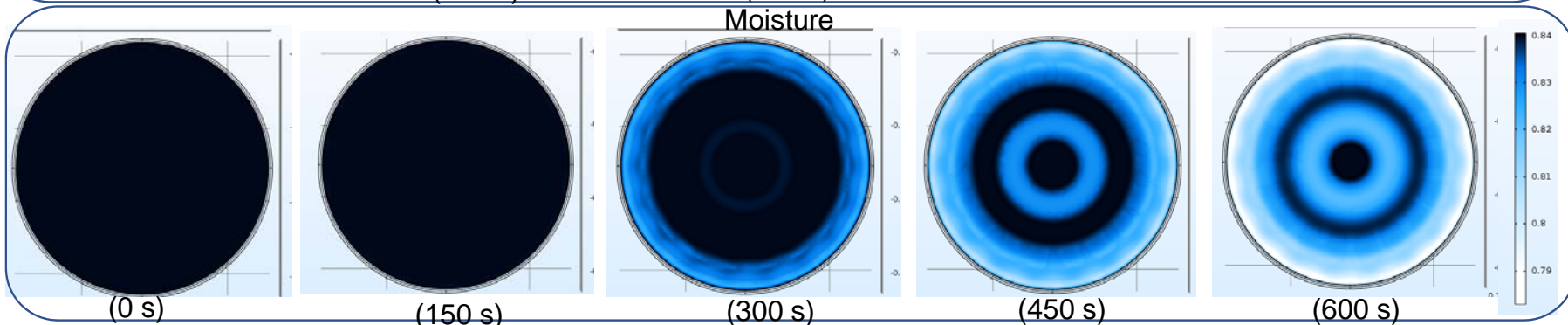
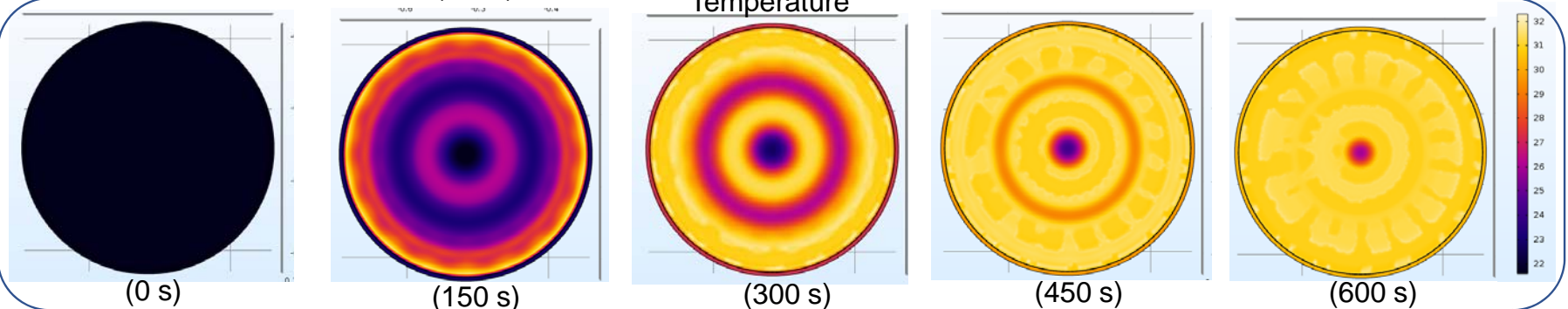
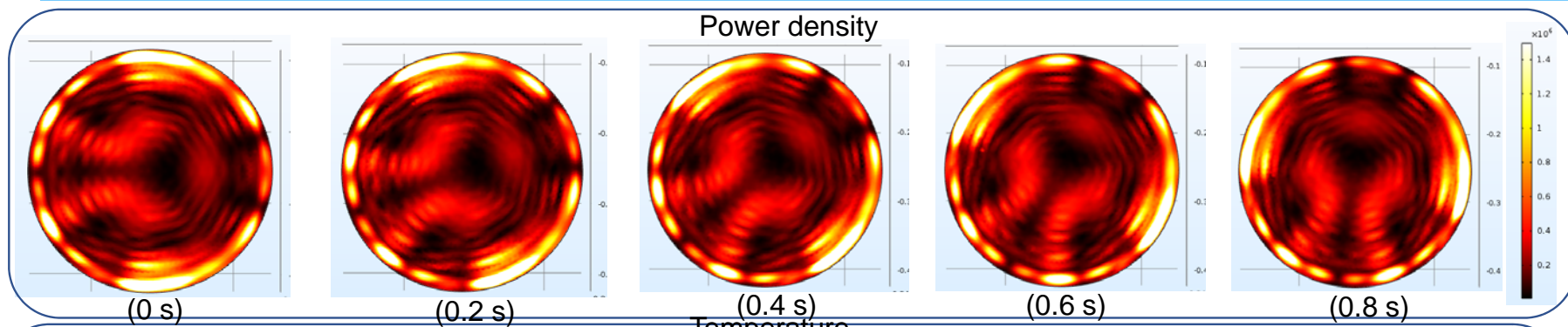
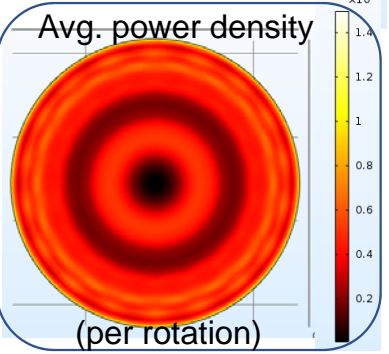
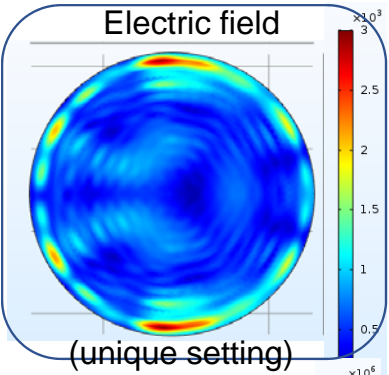
$$\rho = f(\theta_l)$$

$$\dot{\epsilon} = \epsilon' - j\epsilon'' = f(\theta_l, T)$$

$P = 800\text{ W}$
 $f = 2.45\text{ GHz}$



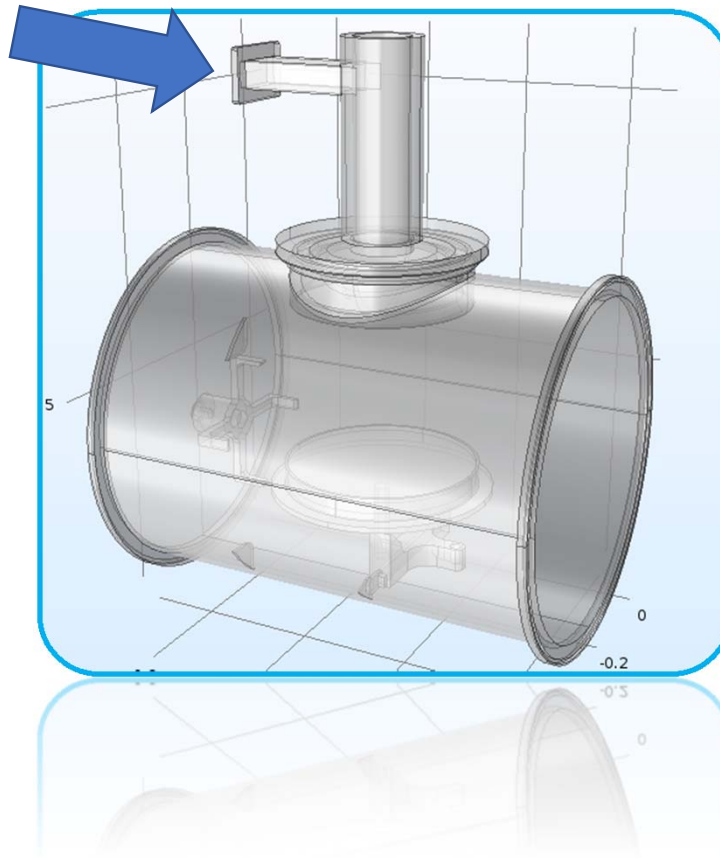
Degrees of freedom in terms of electric field patterns are solely related to the rotation of the turntable.



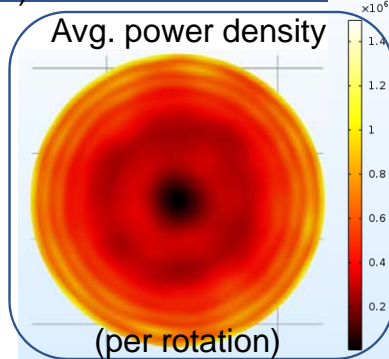
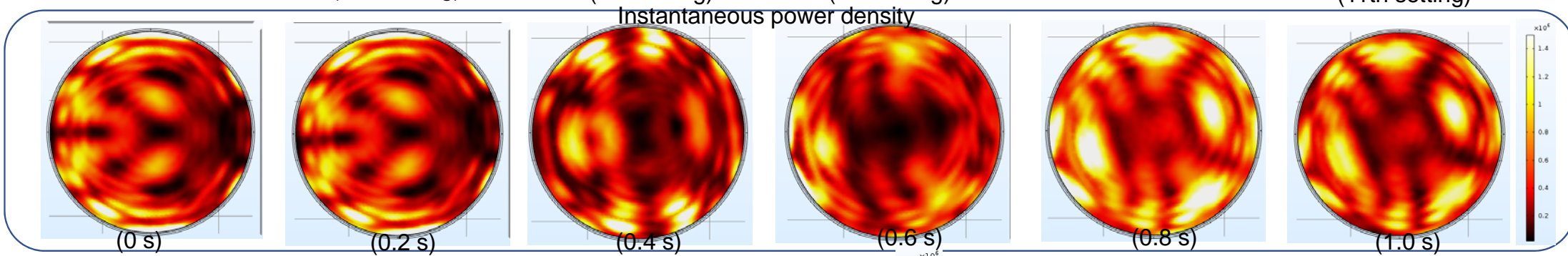
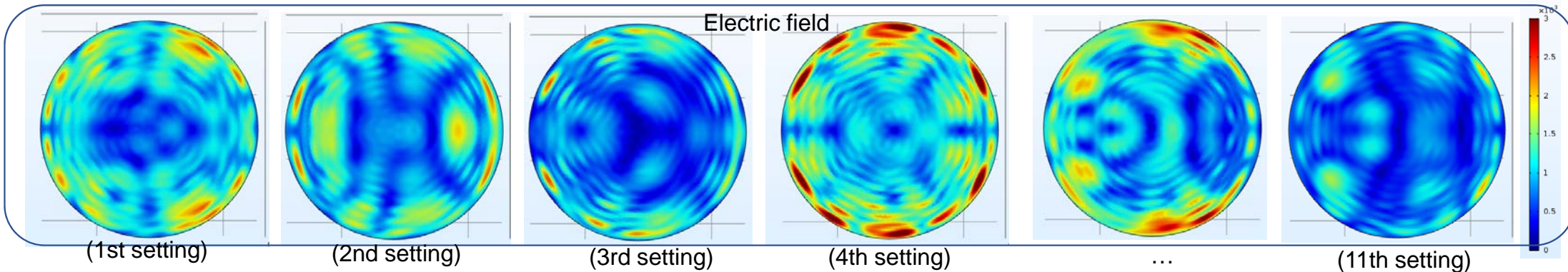
$P = 800\text{ W}$
 $f = [2.4; 2.5]\text{ GHz}$

In the current case: 11 frequency combinations

(tested) 11 electric field patterns

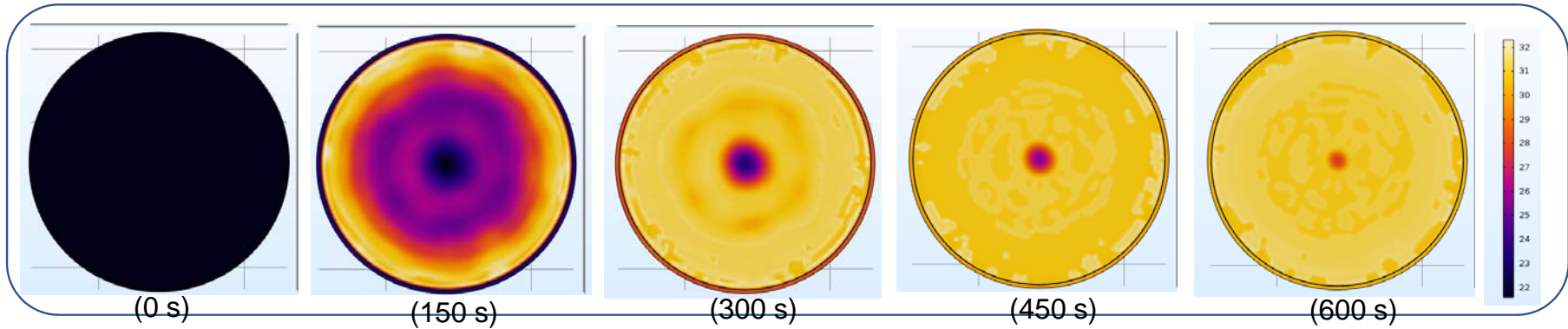


Degrees of freedom in terms of electric field patterns are related to the combination of rotation of the turntable and frequency shift.

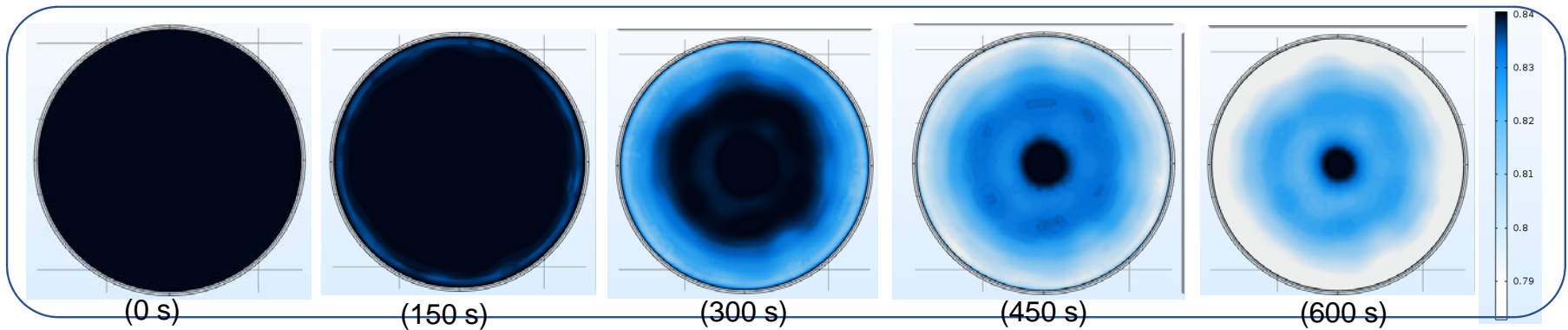


NOTE: Here just a ***sub-sampling*** of all the possible electric field patterns is displayed

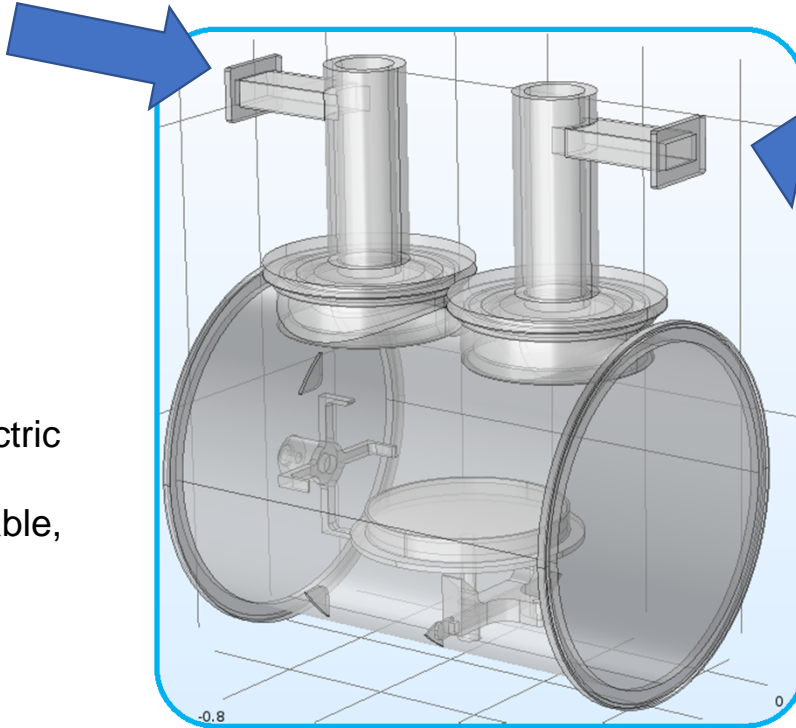
Temperature



Moisture



$$P_1 = 400 W$$
$$f = [2.4; 2.5] GHz$$
$$\phi_1 = 0$$

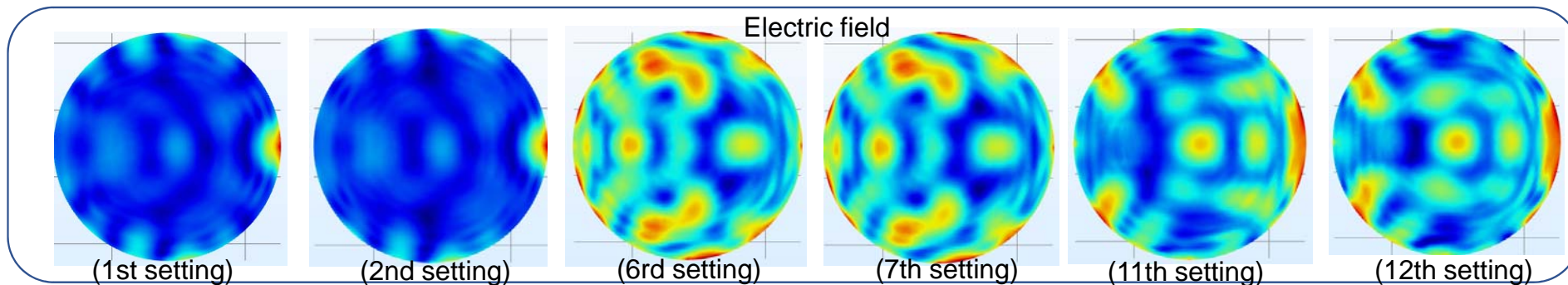


$$P_2 = 400 W$$
$$f = [2.4; 2.5] GHz$$
$$\phi_2 = [0; 360]^\circ$$

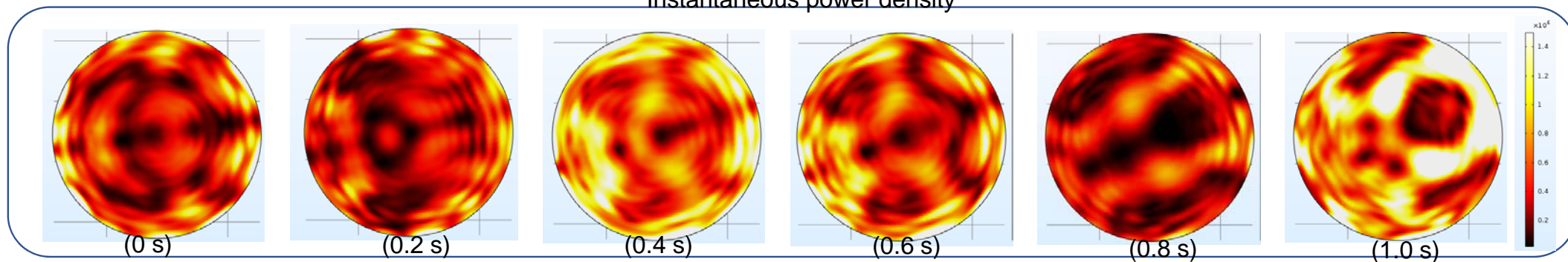
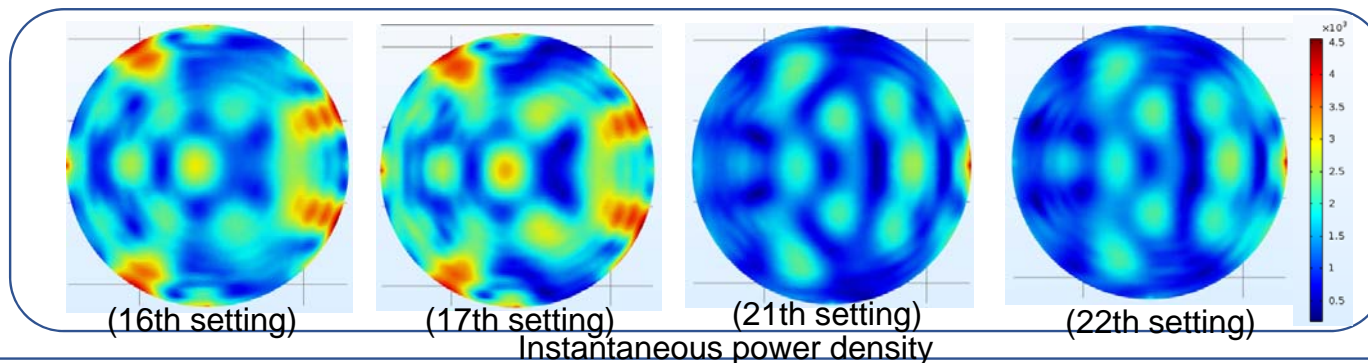
Degrees of freedom in terms of electric field patterns are related to the combination of rotation of the turntable, frequency shift and phase shift.

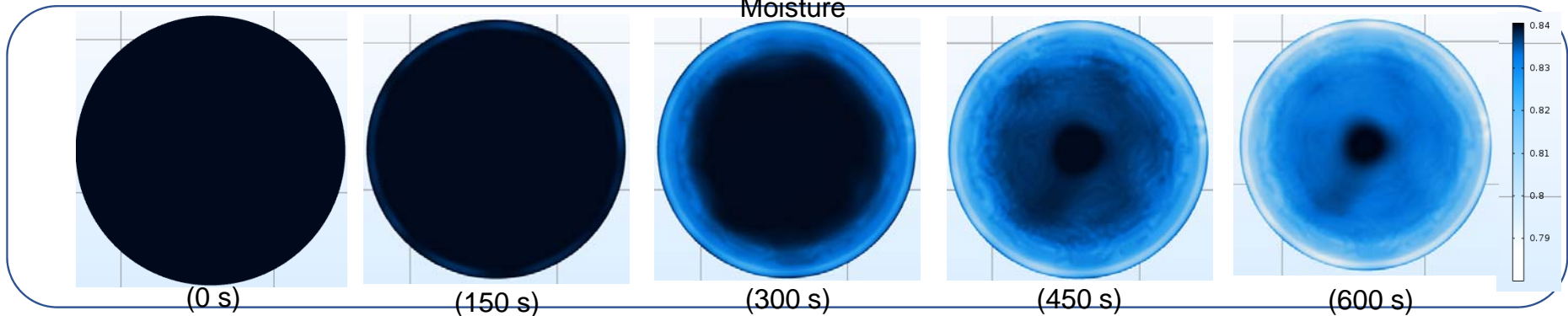
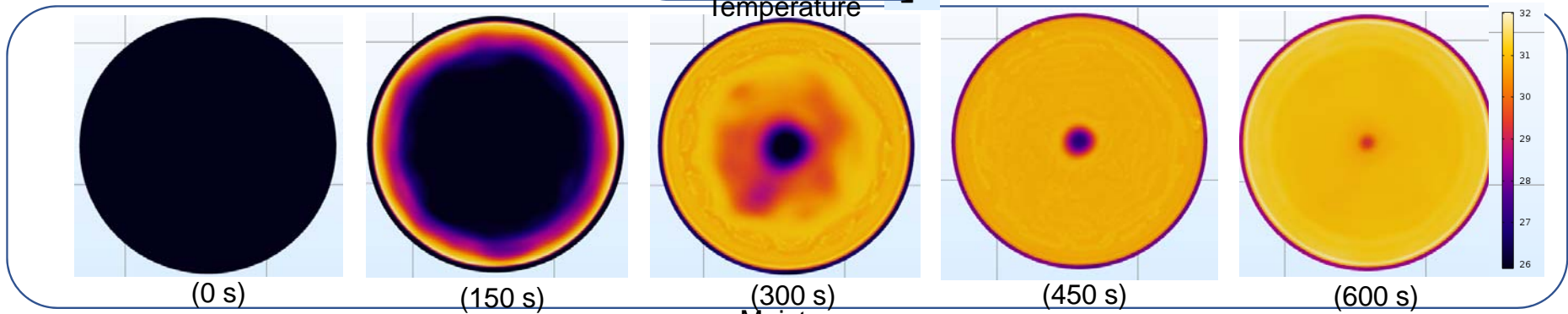
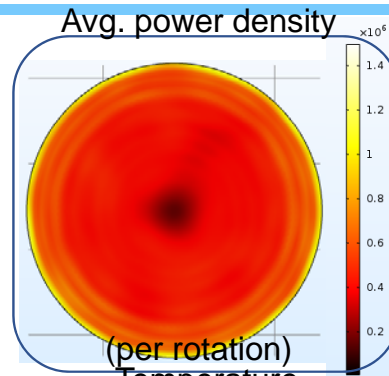
In the current case: 5 frequency combinations are combined with 5 phase shift combinations

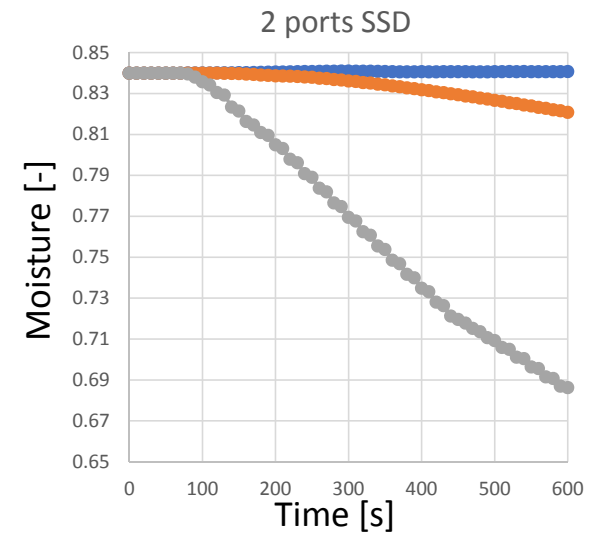
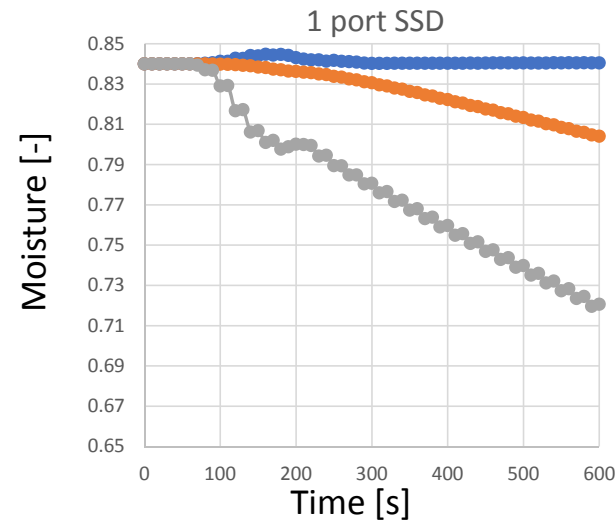
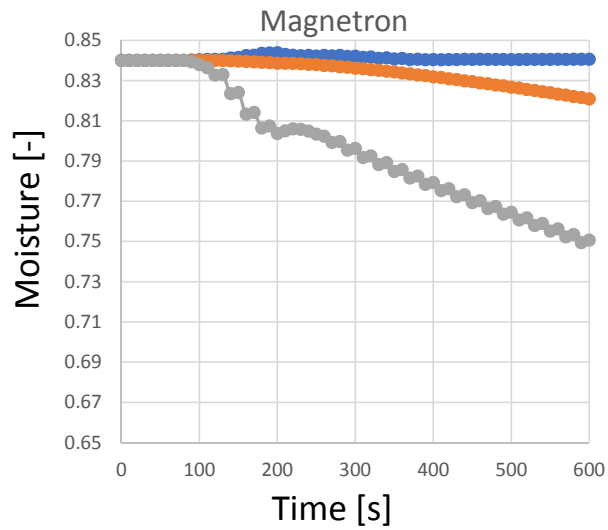
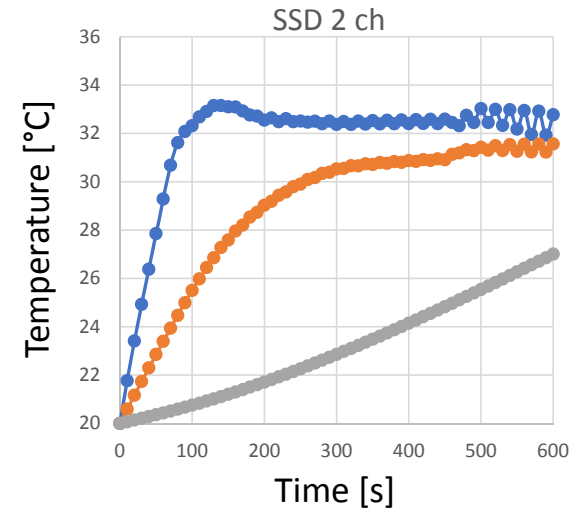
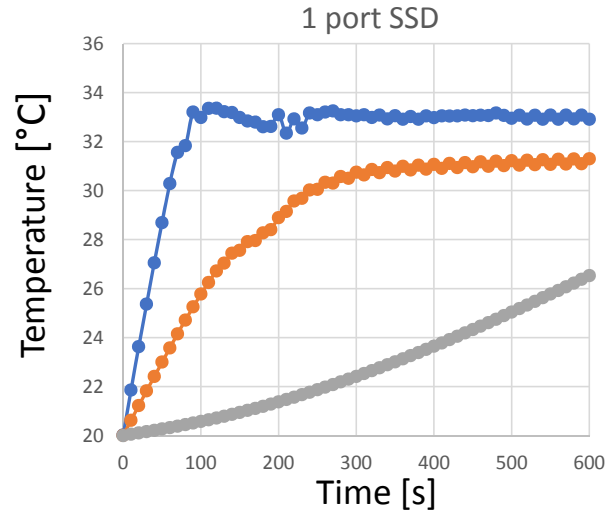
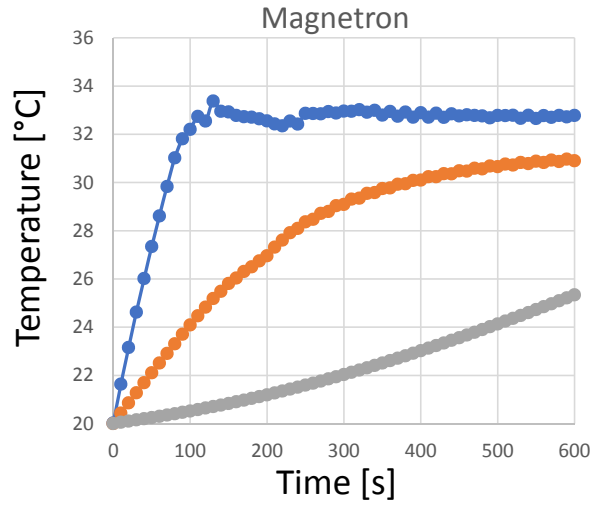
(tested) 25 electric field patterns



NOTE: Here just a **sub-sampling** of all the possible electric field patterns is displayed







- Comsol Multiphysics® Software allows to implement in a very ***flexible*** way complex processes to compare technology performances and to perform product optimization

(e.g., LiveLink™ for Matlab®, PDE interfaces,...)

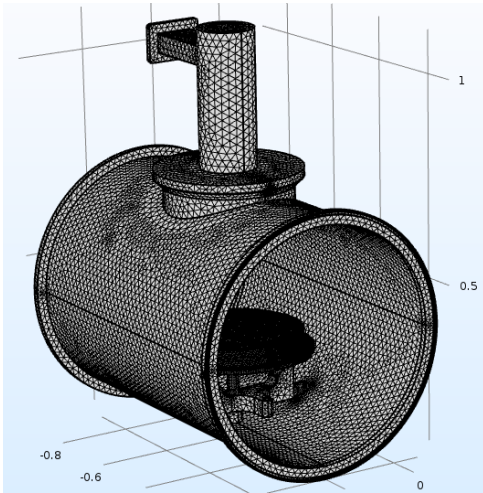
- ***Solid state MW*** processing can guarantee ***higher uniformity*** with respect to classical magnetron based processing
- ***Increasing the number of input ports***, it is possible to achieve further ***more homogeneous*** field patterns.

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Thank you for your kind attention

gigatherm
Focused on Taste

Mesh



Rotation + Vacuum Drying

100460 domain elements
22252 boundary elements
472 edge elements

Heat Transfer

132120 domain elements
30120 boundary elements
1404 edge elements

Electromagnetics

1120903 domain elements
106398 boundary elements
8535 edge elements

NODOF

Heat Transfer + Vacuum Drying

377002 (plus 30481 internal DOFs)

5 minutes, 47 seconds

1st order shape function
(nodal discontinuous Lagrange)

Direct solver PARDISO

Rotation

332994 (plus 43165 internal DOFs).

1 hour, 50 minutes, 29 seconds

2nd order shape function (Lagrange)

Direct solver PARDISO

Electromagnetics

1476970

7 minutes, 23 seconds

1st order shape function (Lagrange)

Direct solver PARDISO