



STUDY OF SPECTRA WITH LOW-QUALITY RESONANCE PEAKS

Application for plant investigation platforms

03.06.2019 | VIKTOR A. SYDORUK

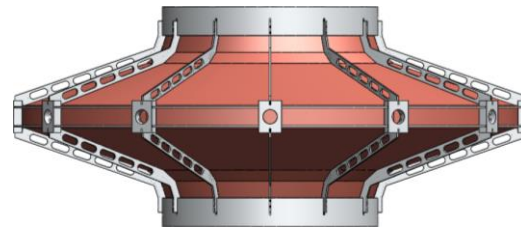
MOTIVATION

for development of Microwave/Radio Frequency resonator based measurement setups

- Noninvasive method: monitoring of plant growth during an extensive period of time.
- Speed: scanning of up to 300 plants per day.
- Sensitivity: possibility to detect changes of $<1\%$ of total plant weight.
- Fully-automatic operation.

RESONATOR BASED MEASUREMENT SETUPS

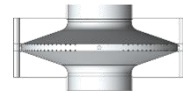
phenoCave GreenHouse:



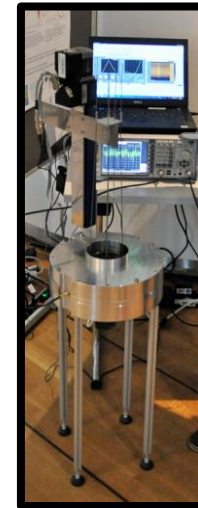
36 cm

width of objects that can be measured

11 cm



phenoCave lab:



V. A. Sydoruk, et al., "Design and Characterization of Microwave Cavity Resonators for Noninvasive Monitoring of Plant Water Distribution," IEEE TMTT (2016) doi: 10.1109/TMTT.2016.2594218.

RESONANCE

In terms of

- **sound....:**

the reinforcement or prolongation of sound by reflection from a surface or by the synchronous vibration of a neighbouring object

- **electricity....:**

the condition in which an electric circuit or device produces the largest possible response to an applied oscillating signal

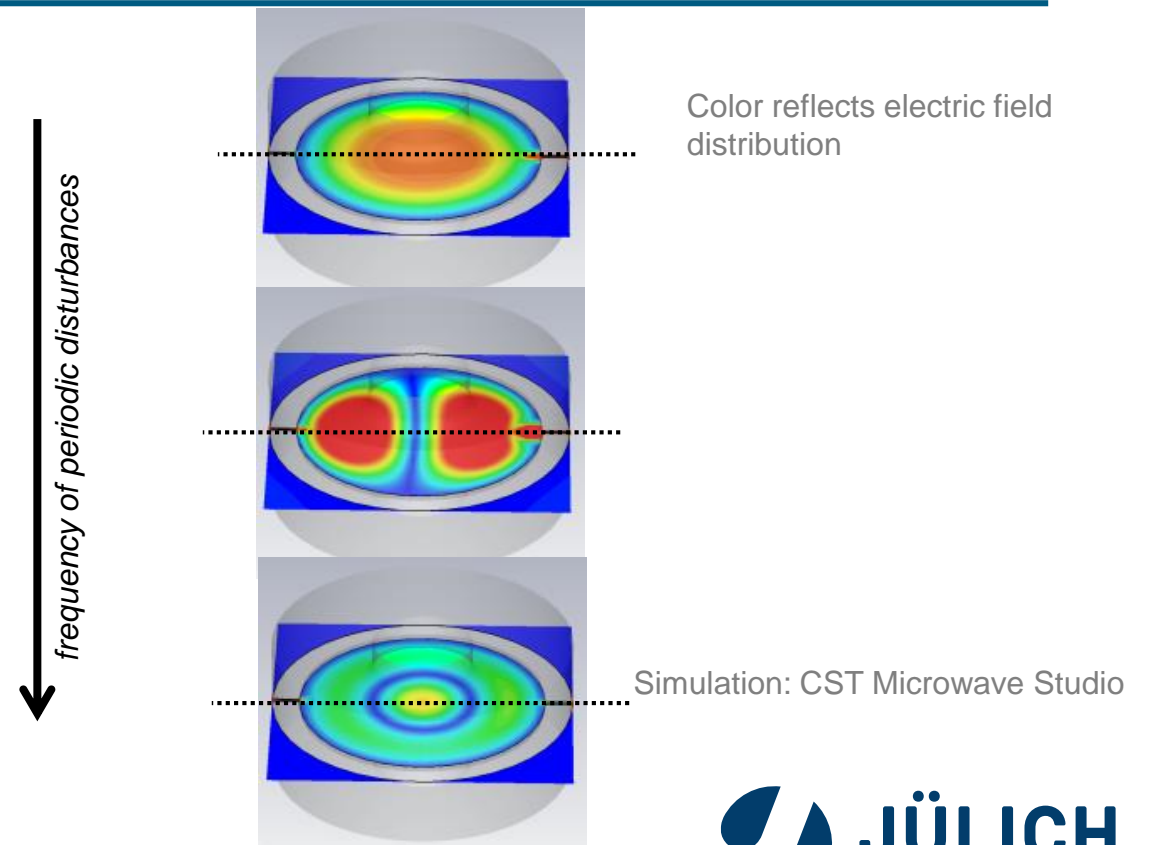
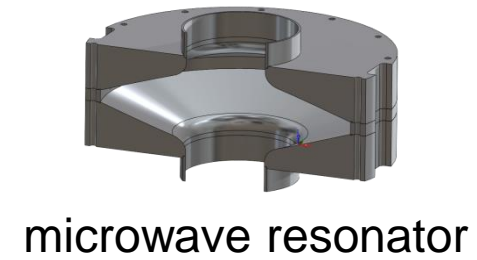
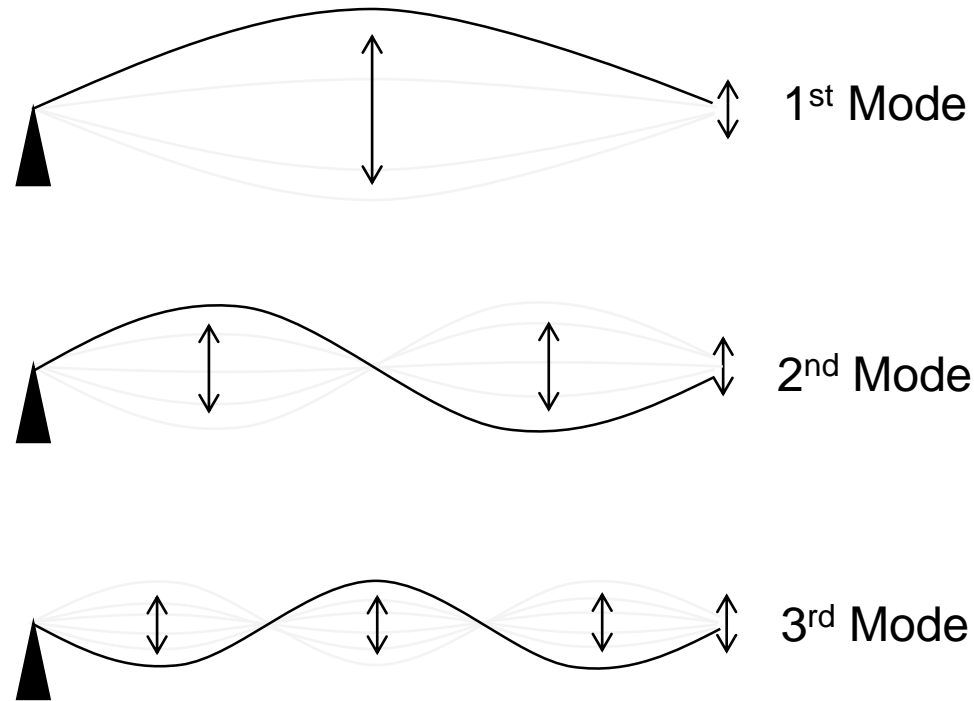
- **mechanics....:**

the condition in which an object or system is subjected to an oscillating force having a frequency close to its own natural frequency

Oxford Dictionary

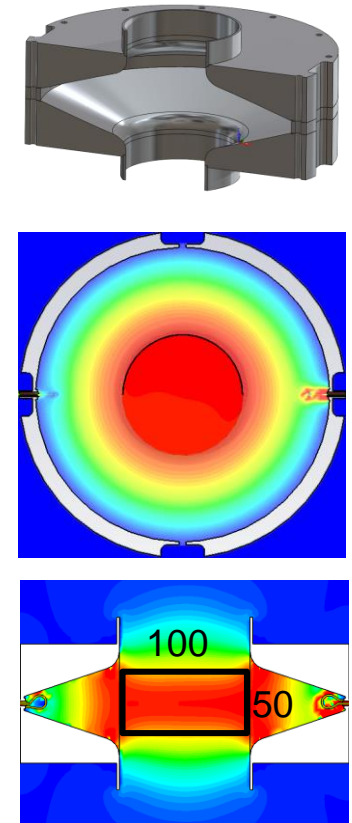
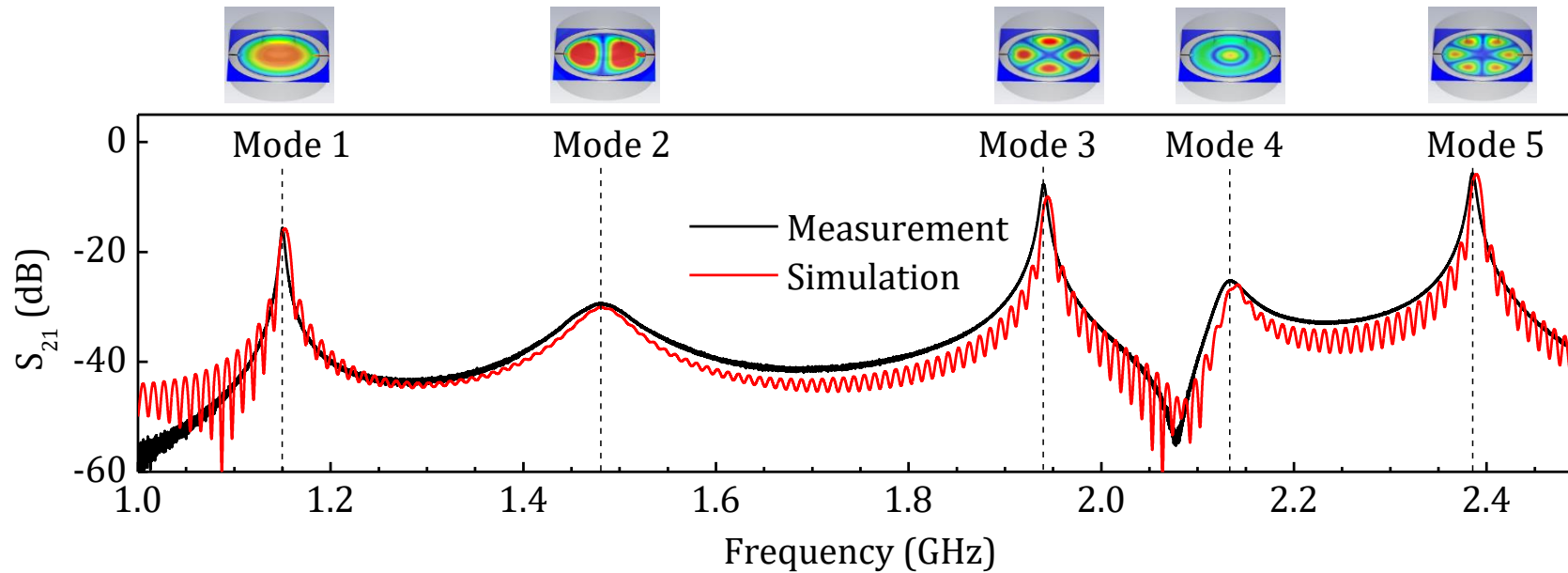
RESONANCE MODES

elastic band



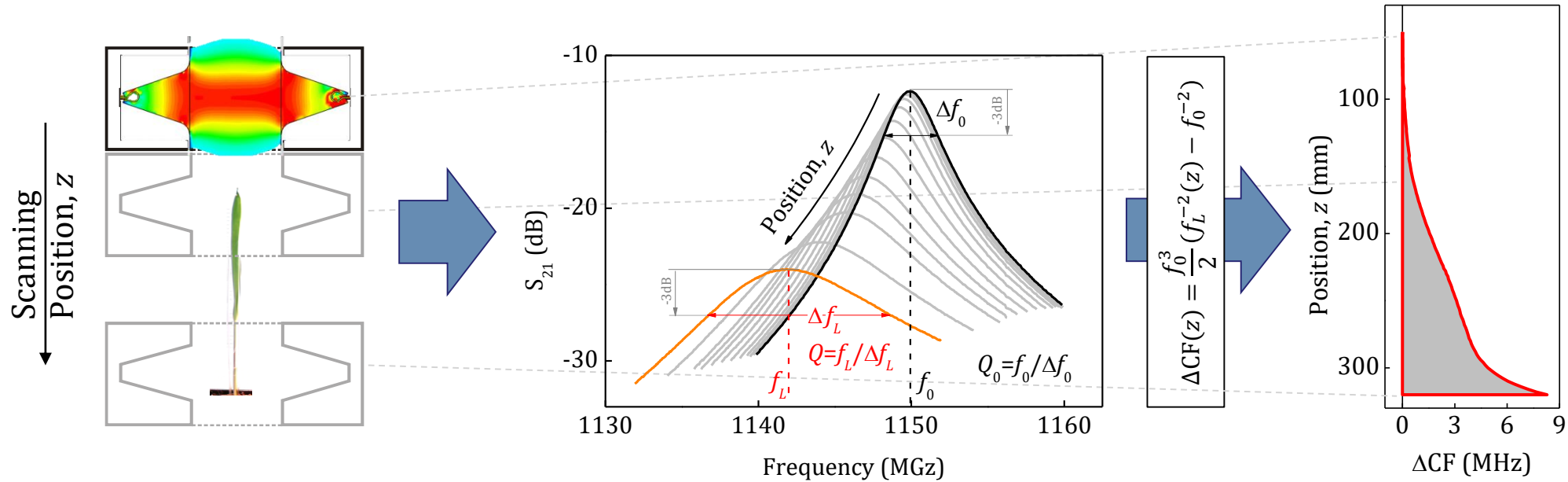
RESONANCE MODES

Measured and simulated spectra of unloaded resonator



Simulation: CST Microwave Studio

MEASUREMENT PRINCIPLE



Estimation of

- Water Amount (WA): $\frac{f_0^3(z)}{2} (f_L^{-2}(z) - f_0^{-2}(z)) \sim WA(z)$

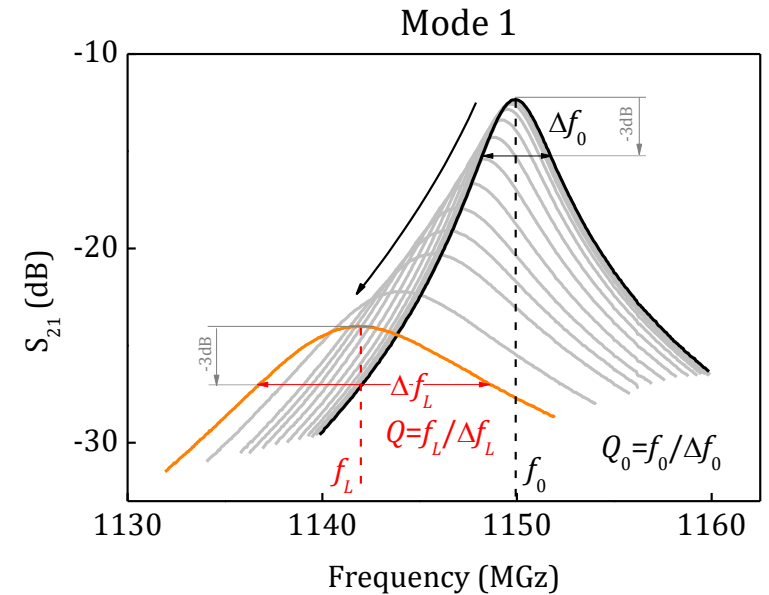
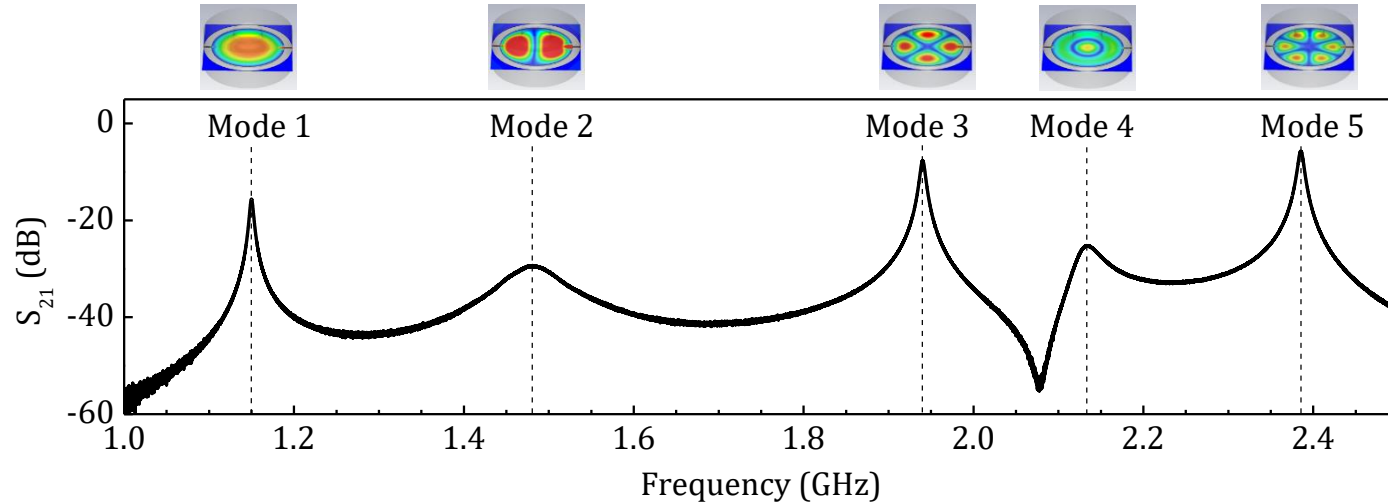
$$\int_{-\infty}^{\infty} \frac{f_0^3(z)}{2} (f_L^{-2}(z) - f_0^{-2}(z)) dz \sim WA_{total}$$

- Dry Weight (DW): $\frac{f_0^2(z)}{2f_L(z)Q_0(z)} \left(\frac{f_0(z)Q_0(z)}{f_L(z)Q_L(z)} - 1 \right) \sim DW(z)$

$$\int_{-\infty}^{\infty} \frac{f_0^2(z)}{2f_L(z)Q_0(z)} \left(\frac{f_0(z)Q_0(z)}{f_L(z)Q_L(z)} - 1 \right) dz \sim DW_{total}$$

FITTING OF SPECTRA

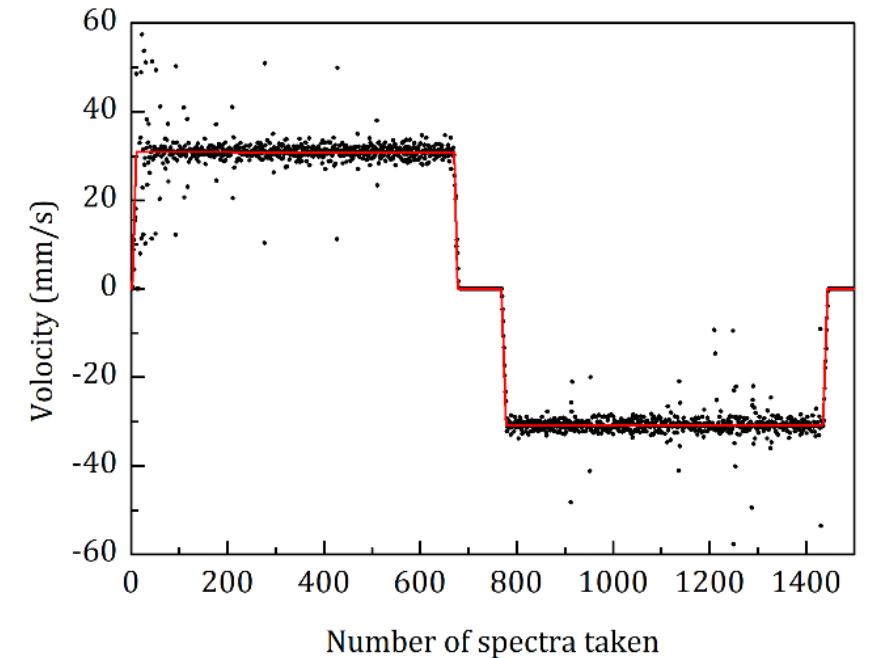
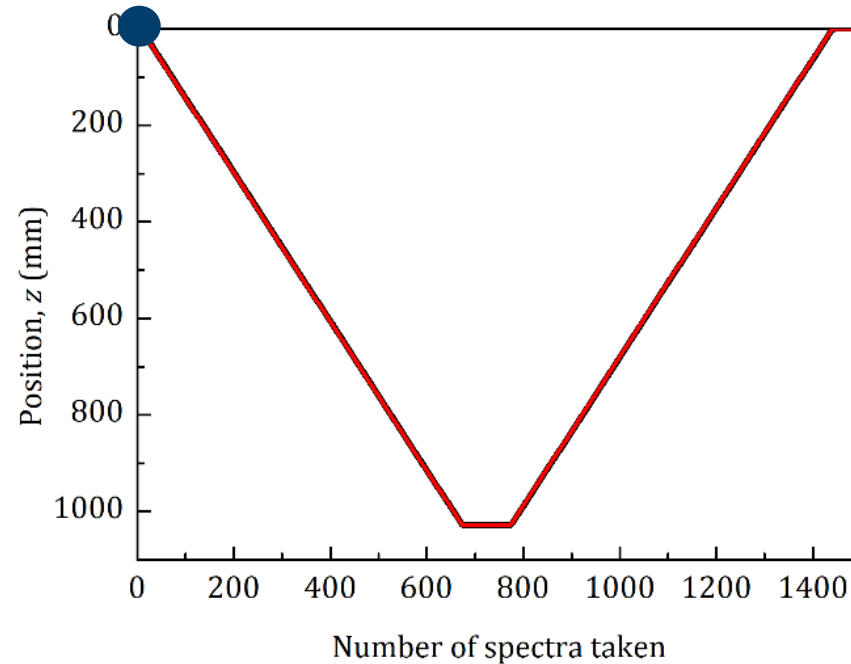
Issues



1. **Time delays** between position of a resonator and spectra points readings when the resonator moves continuously without intermediate stops.
2. Influence of **higher modes**.
3. **Impossibility** to ideally **calibrate** a vector network analyzer (especially for the Greenhouse setup).
4. Influence of **cables** and **surroundings**.

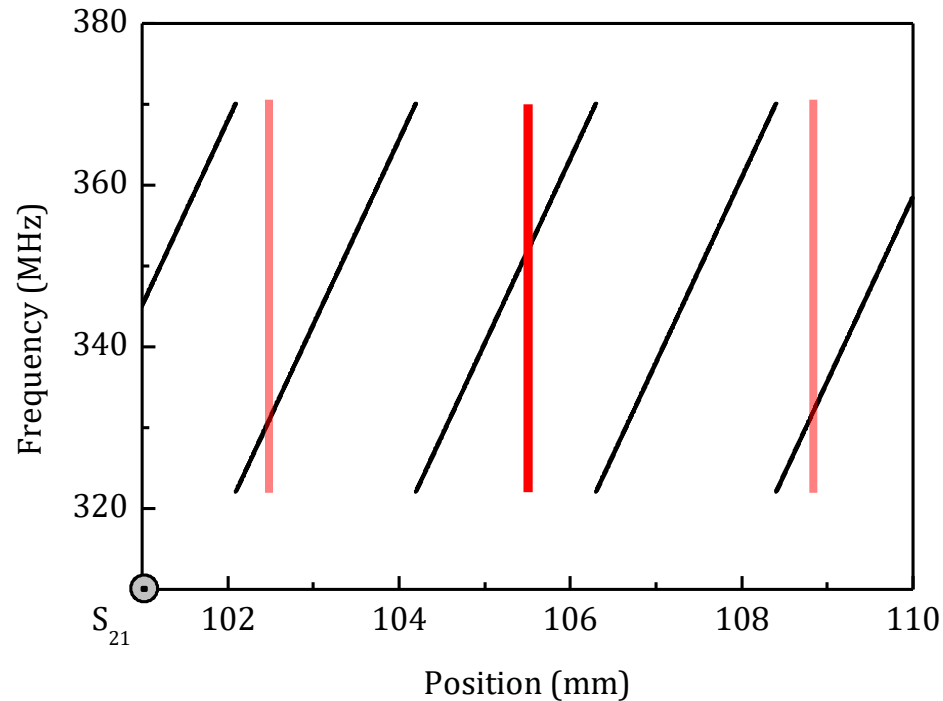
SPECTRA PREPARATION

1. When a resonator is continuously moving while receiving the spectra



SPECTRA PREPARATION

1. When a resonator is continuously moving while receiving the spectra



Each spectrum is recalculated using neighboring measured spectra (polynomial fit at the same frequency)

Additional **pros**:

- automatically smoothed spectrum
- possibility to detect outliers in combination with the Grubbs' test.

FITTING OF SPECTRA

2. Approaches

Lorentzian approach

$$\Gamma_i(f) = \frac{A_i}{\sqrt{1 + 4Q_i^2 \tau_i^2(f)}}$$

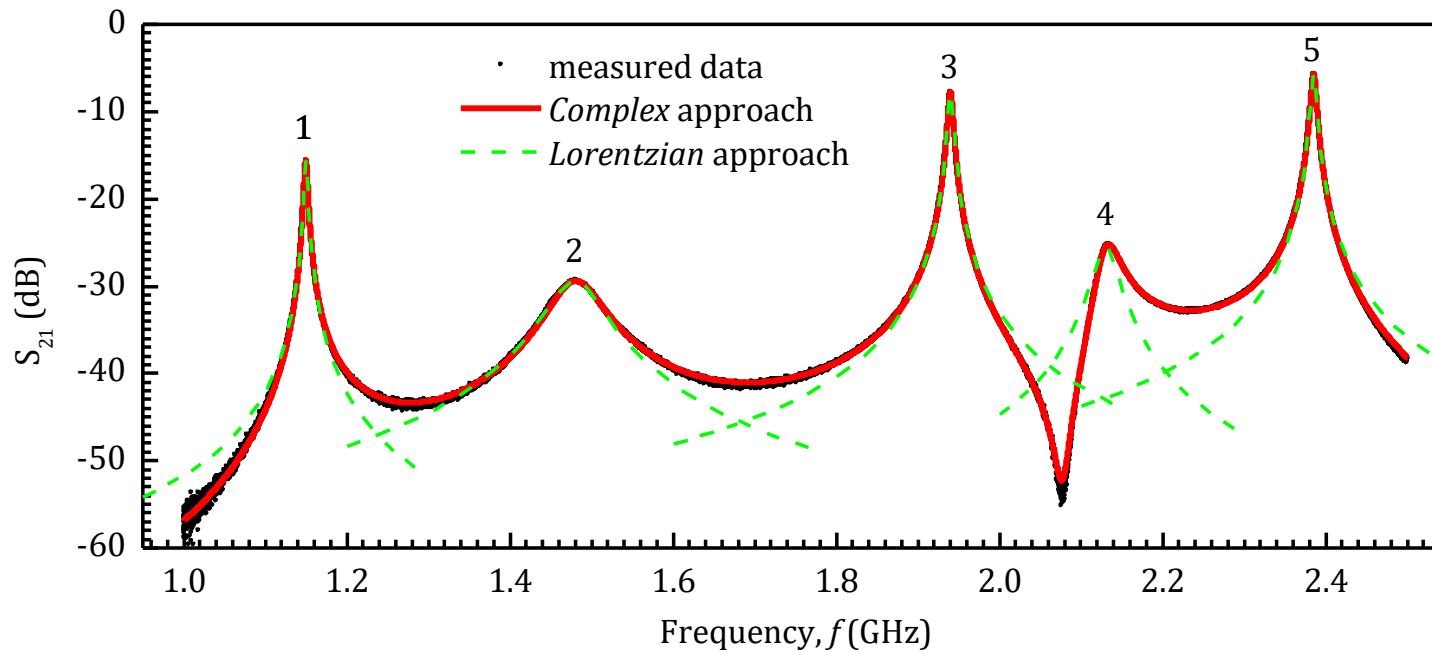
Complex approach

$$\Gamma(f) = \Gamma_s + \sum_i^n \frac{A_i \exp(j\phi_i)}{1 + 2jQ_i \tau_i(f)}$$

Note:

$$S_{21}(f) = 20 \cdot \log_{10}(|\Gamma(f)|/\Gamma_0)$$

$$\tau_i(f) = (f - f_{0i})/f_{0i}$$



FITTING OF SPECTRA

2. Comparison of different approaches; influence of higher modes

Lorentzian approach

$$\Gamma_i(f) = \frac{A_i}{\sqrt{1 + 4Q_i^2 \tau_i^2(f)}}$$

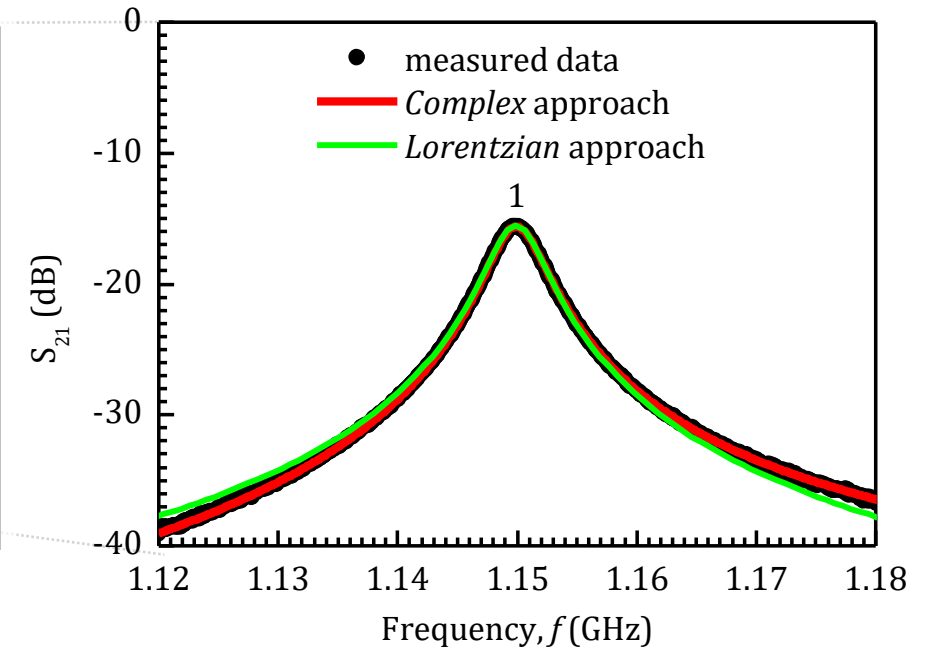
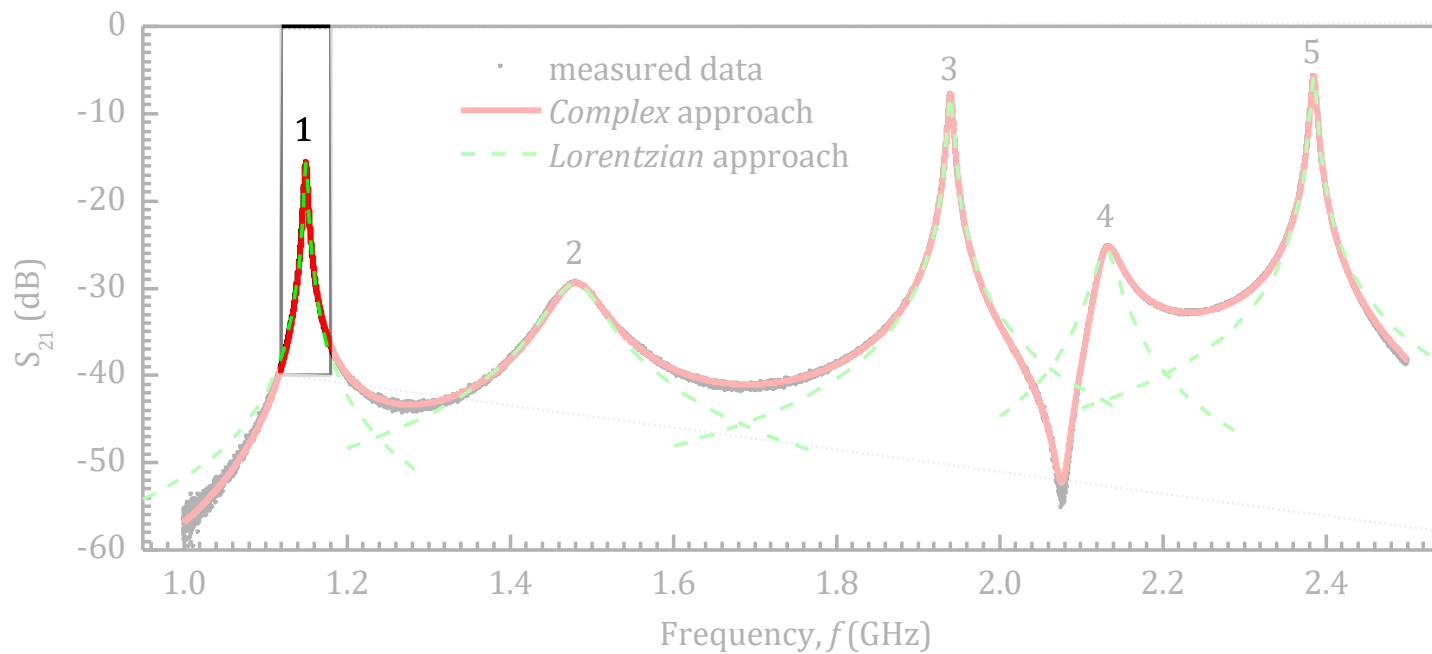
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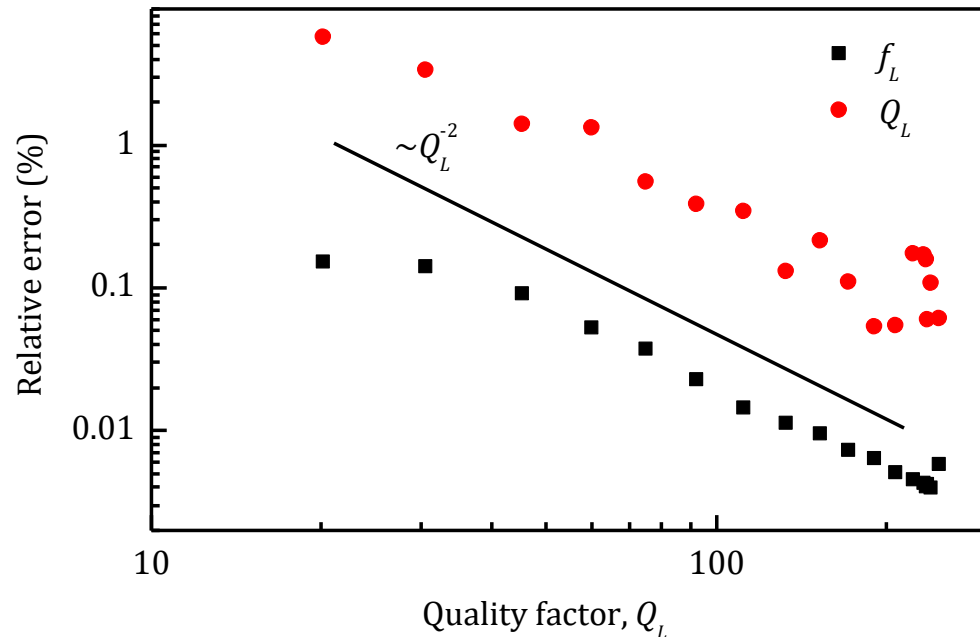


FITTING OF SPECTRA

2. Influence of higher modes

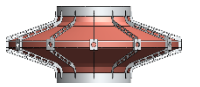
$$\text{Relative error} = |p_{\text{complex}} - p_{\text{Lorentzian}}| / p_{\text{complex}} \times 100\%$$

where p is either resonant frequency f_L or quality factor Q_L of a loaded resonator.



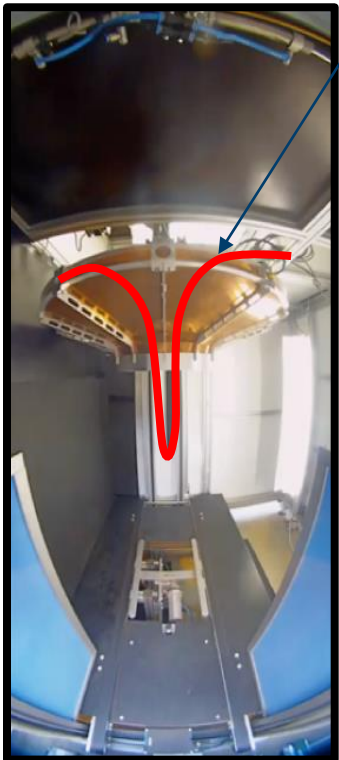
In terms of the plant Water Amount (WA):

- 0.2% of f_L is 2.3 MHz for phenoCave GreenHouse resonator, or $\sim 1.5 \mu\text{L}/\text{mm}$, which is for a young maize plant of 2 g fresh weight and about 200 mm height gives 0.3 mL of WA \Rightarrow 16% of error for the plant WA estimation.



RESIDUALS

3. Impossibility to ideally calibrate a vector network analyzer (especially for the Greenhouse setup)



cables

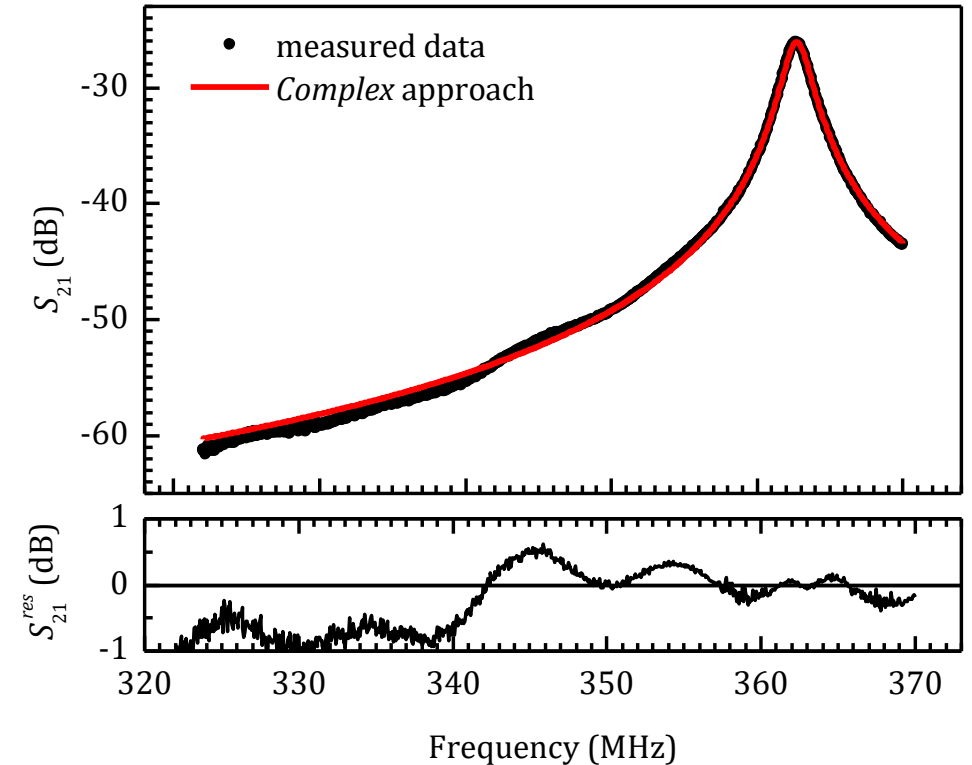
Reasons:

- Long cables.
- Resonator movements.

Residuals have periodic behavior, which should be taken into account.

$$S_{21}^{res}(f) = \sum_i^k a_{i\sin} \sin(2\pi f / f_{i\sin} + \varphi_{i\sin})$$

*Initial values obtained using FFT

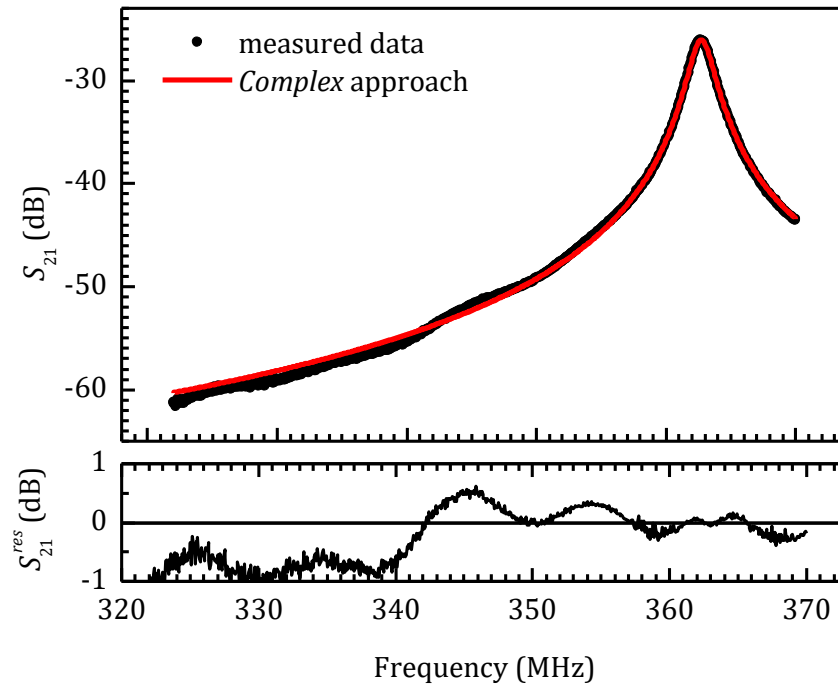


RESIDUALS

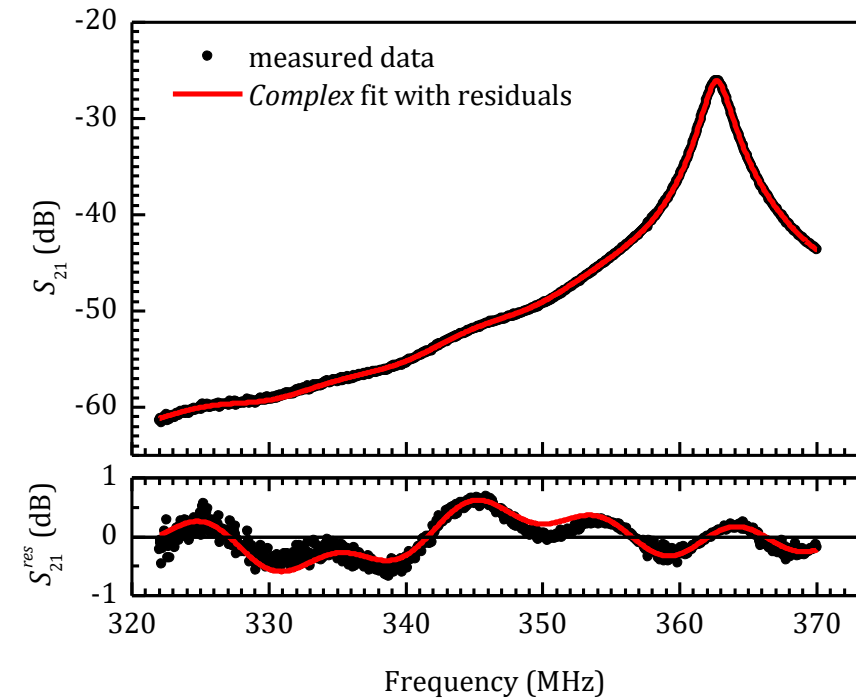
3. Fitting of residuals

Obtained parameters:

$$f_0 = 362.700 \pm 0.002 \text{ MHz } Q_0 = 191.0 \pm 0.4$$



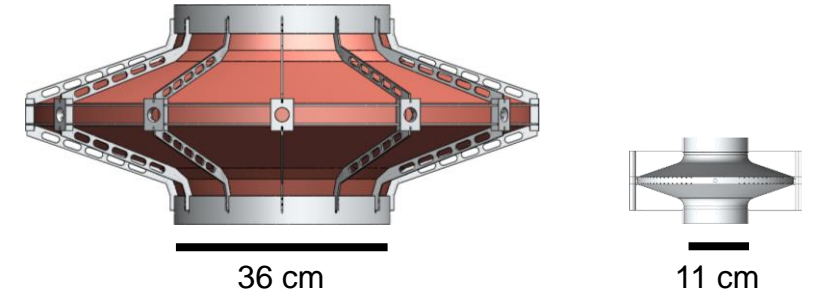
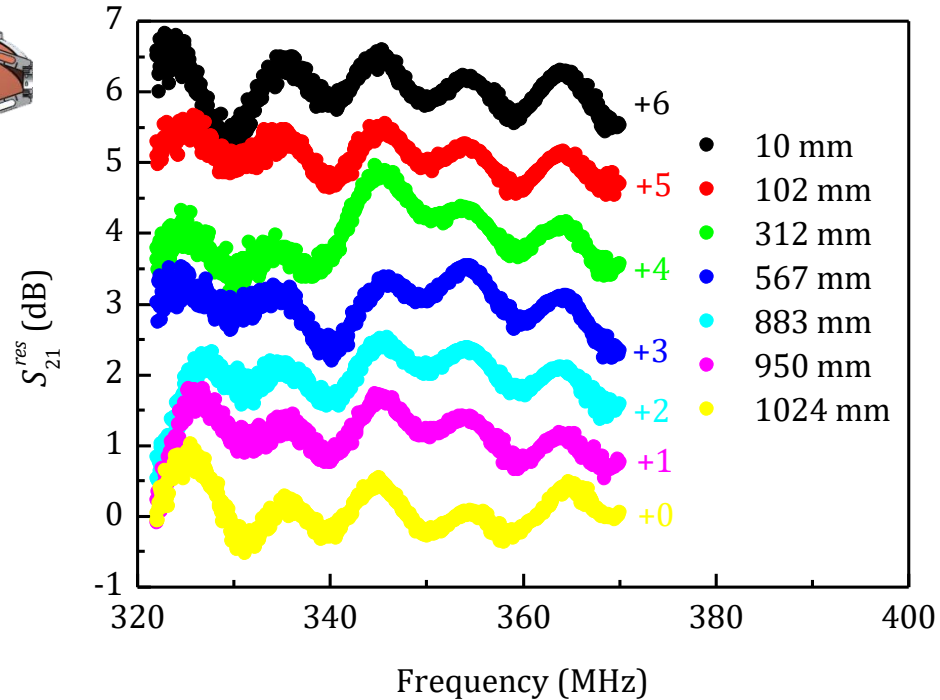
$$f_0 = 362.675 \pm 0.002 \text{ MHz } Q_0 = 187.1 \pm 0.3$$



RESIDUALS

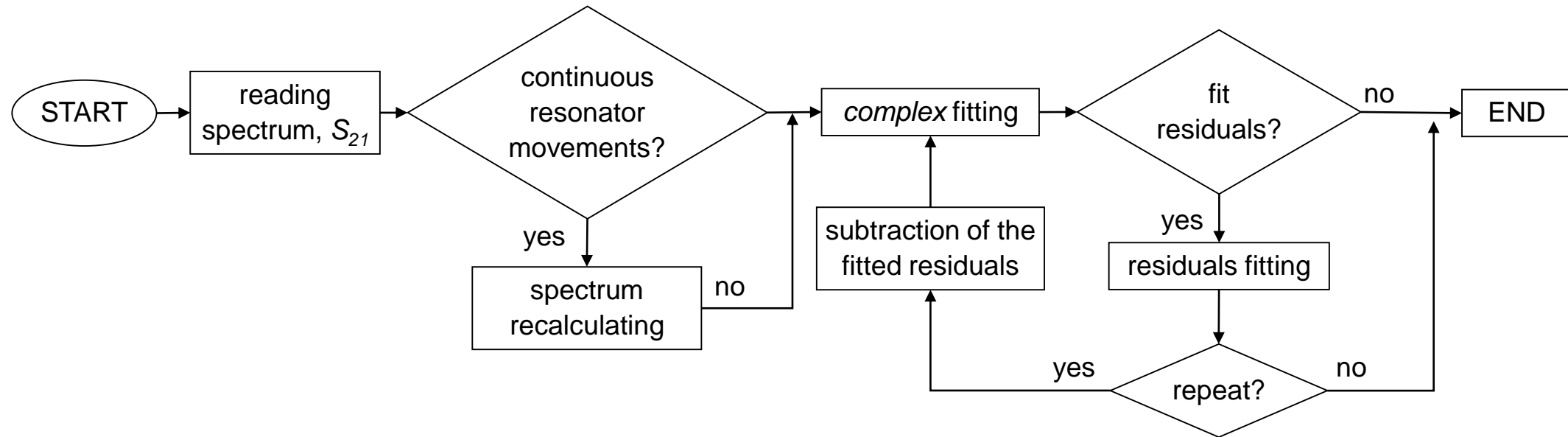
4. Influence of cables and surroundings

- Residuals depend on the position of a resonator due to large openings.



- Residuals from empty runs are used to fit spectra of loaded resonator (when a plant is measured)

SPECTRUM FITTING ROUTINE



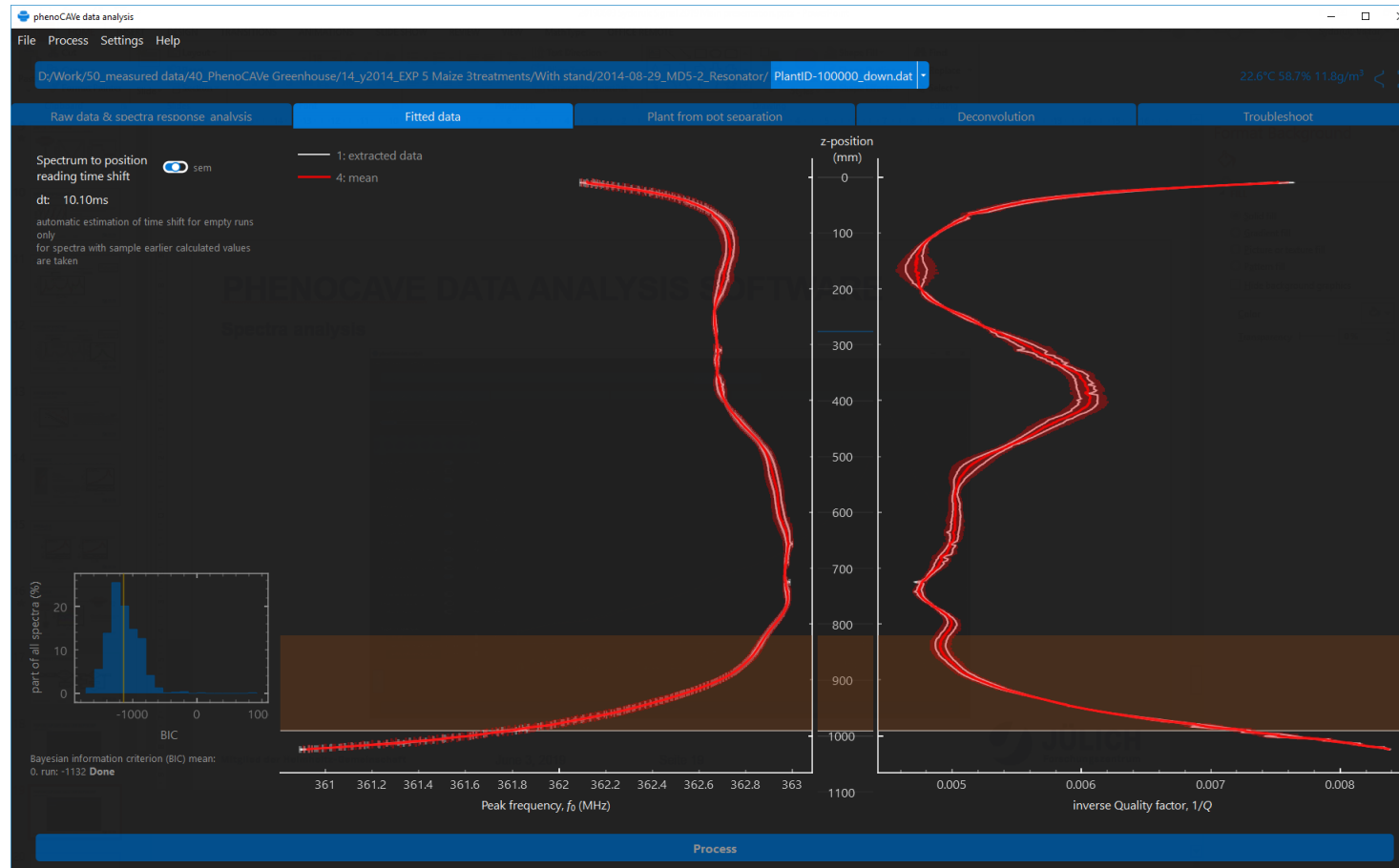
PHENOCAVE DATA ANALYSIS SOFTWARE

Spectra analysis



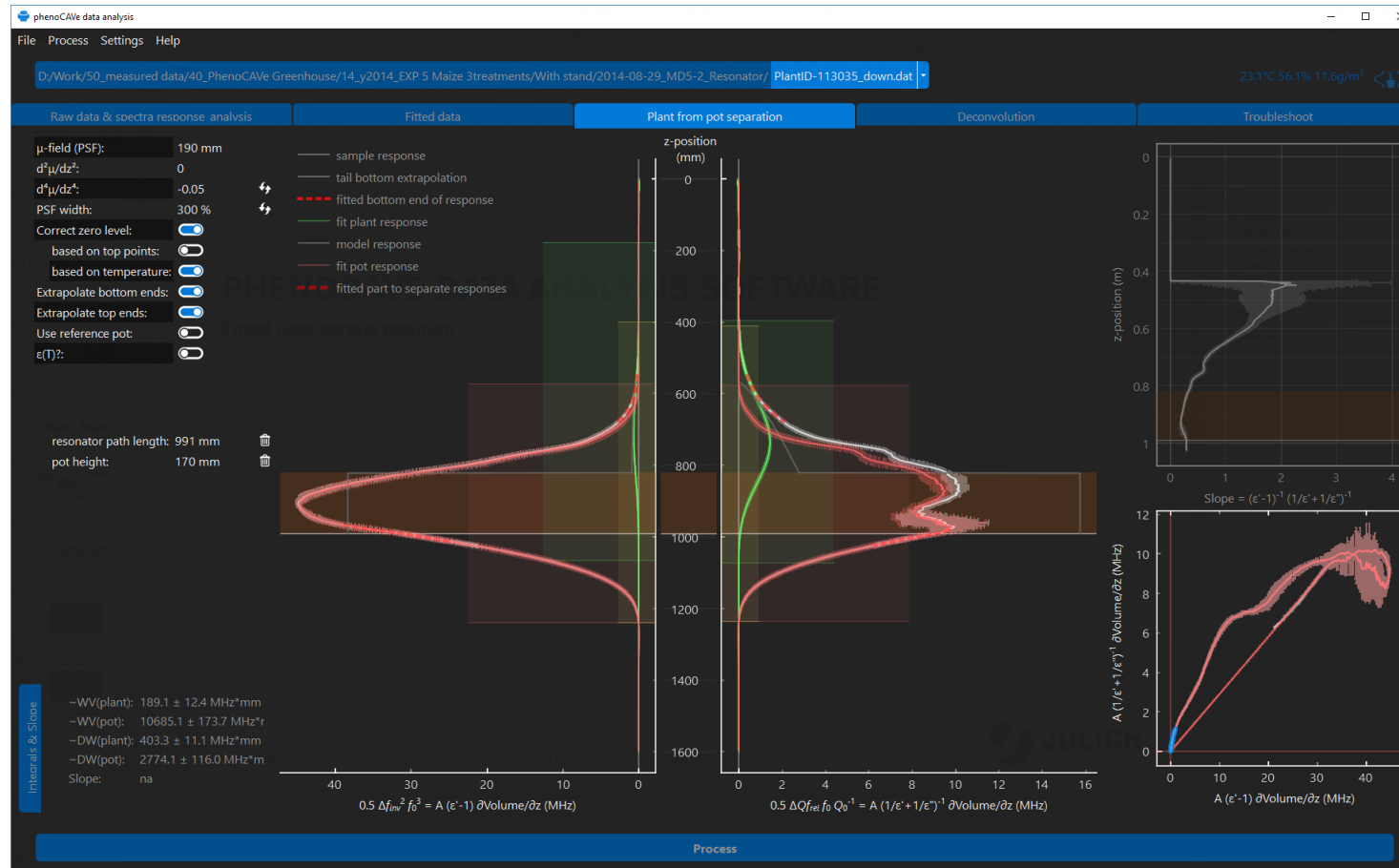
PHENOCAVE DATA ANALYSIS SOFTWARE

Fitted data versus position



PHENOCAVE DATA ANALYSIS SOFTWARE

Extracting of WA and DW for a measured plant



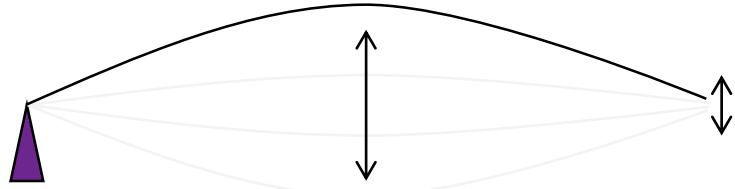
CONCLUSIONS

- The fitting approach is mainly developed to analyze low-quality resonance peaks on measured spectra.
- The simple *Lorentzian* fitting approach is compared with the *complex* one, to which a preference was given.
- Issues that may arise during the measurements using partially opened resonators are shown and discussed with their possible resolution.
- Among them are the influences of other modes, surroundings, cables, and continuous movements of either a resonator or an investigated object.
- The spectrum fitting routine was suggested and the software based on it was demonstrated.
- The suggested *complex* fitting approach is not newly developed but the proposed fully automated fitting routine has novel ideas which can be useful for the precise analysis of spectra with low-quality resonance peaks.

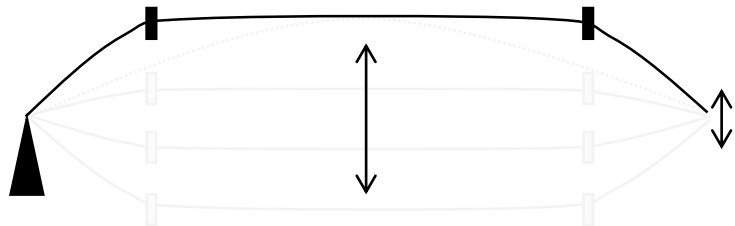
THANK YOU FOR YOUR ATTENTION!

RESONANCE MODES

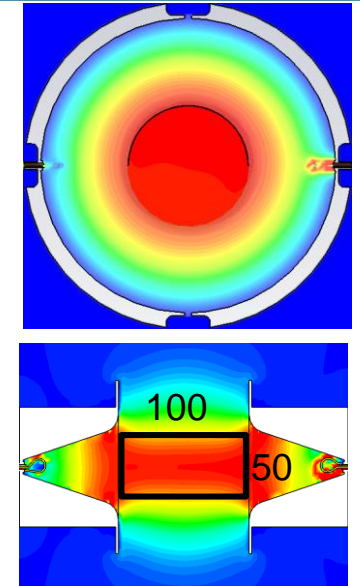
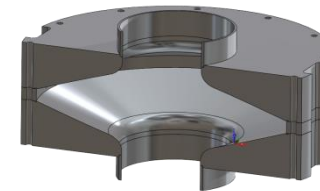
Usage of the 1st mode; electromagnetic field distribution



First prototype



Last prototype



WATER AS A DIELECTRIC MATERIAL

Usage of the 1st mode; electromagnetic field distribution

- Dielectric permittivity

$$\varepsilon' + j\varepsilon''$$

ε' - related to the stored energy;

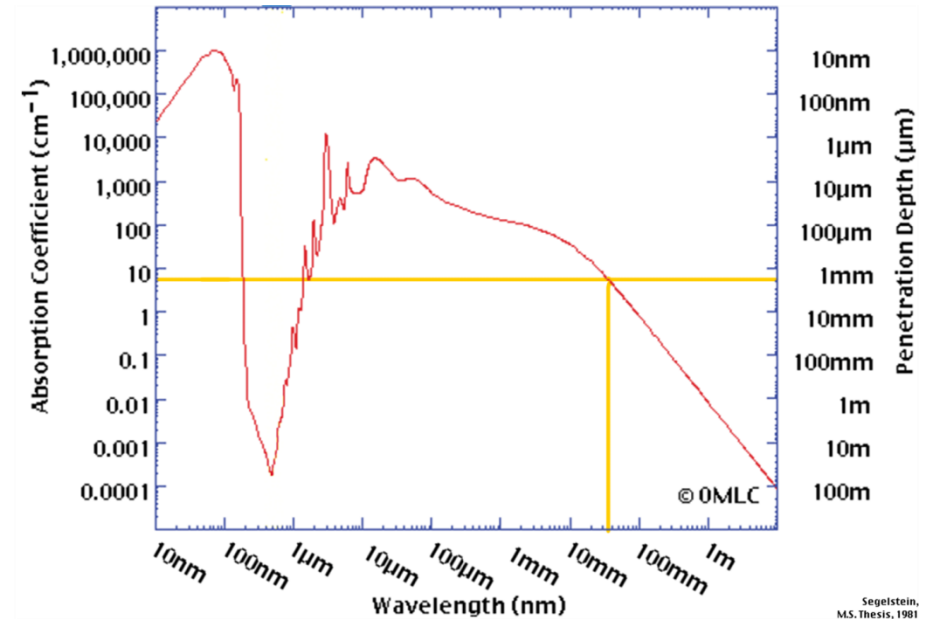
ε'' - related to the dissipation (or loss) of energy.

- Water

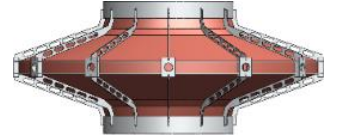
$$\varepsilon' = 78.2 @ 1\text{GHz}$$

$$\varepsilon'' = 3.8 @ 1\text{GHz}$$

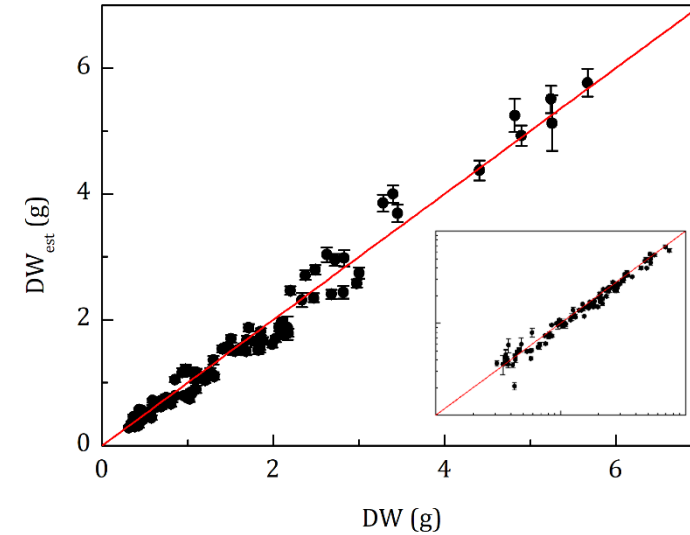
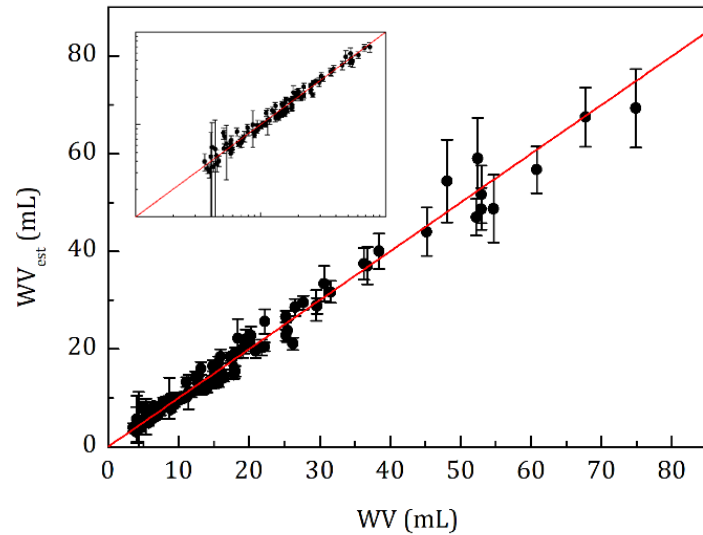
to obtain at least 2 mm penetration depth we should to work at < 7.5 GHz frequencies



RESULTS



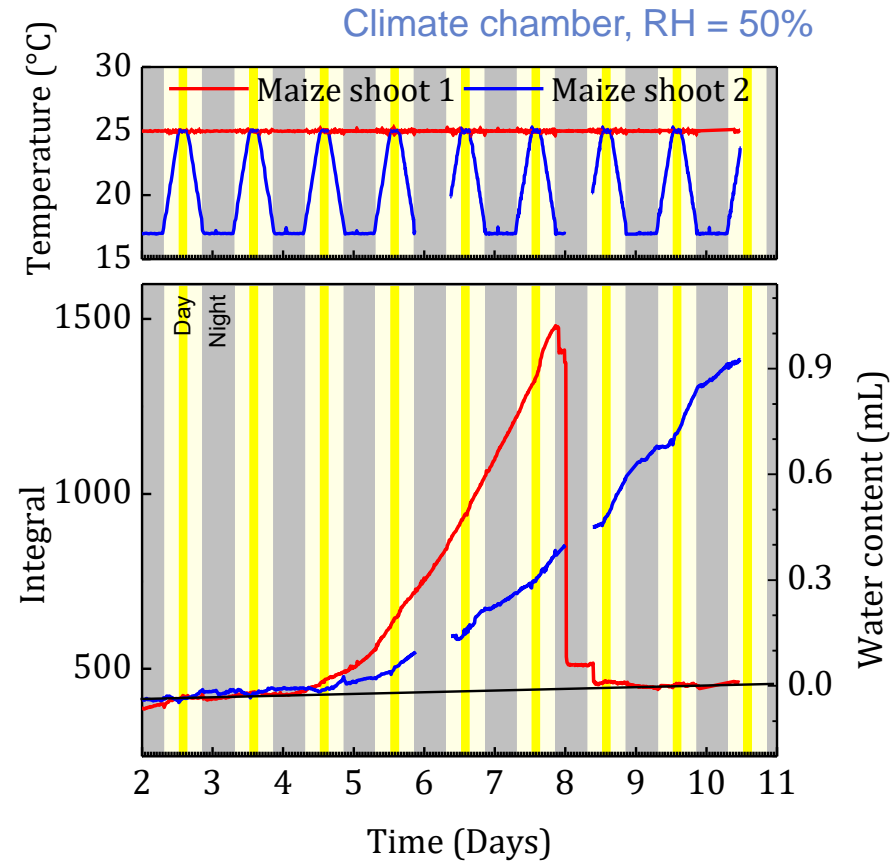
- Estimated by the resonator vs destructively measured data



3 different stresses. Measurements of maize plants using phenoCave Greenhouse

*WV – Total Water Volume, DW – Total Dry Weight

MEASUREMENTS OF MAIZE SHOOTS



RESPONSES FROM DIFFERENT PARTS OF A PLANT

