Grain-boundary Scattering of Surface Acoustic Waves: Experiment, theory, and Simulation

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Outline

- Grain-Boundary Scattering of Longitudinal Bulk Waves

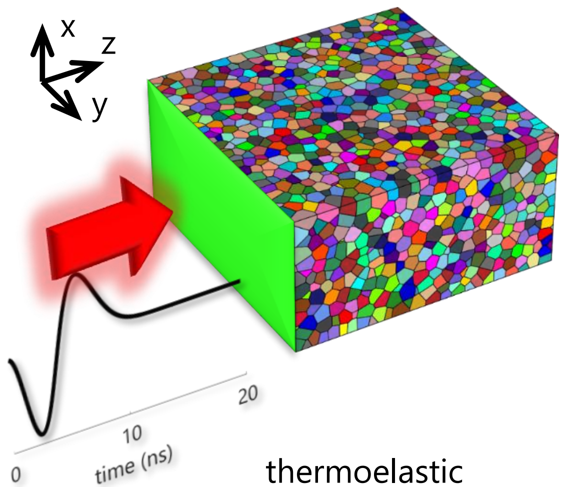
- Grain-Boundary Scattering of Surface Acoustic Waves

FEM simulation of L-wave scattering

[M. Ryzy et al., J. Acoust. Soc. Am. 143, 219 (2018)]

- Virtual polycrystal: Voronoi tessellation
- Time-domain FEM simulation of L-wave propagation

Tessellation Software: Neper
FEM Software: PzFlex



thermoelastic excitation

8000 grains
$1 \times 2 \times 2$ mm^3

375 mil. DoF (12 runs)
el. size 3.2 µm, time step 0.4 ns

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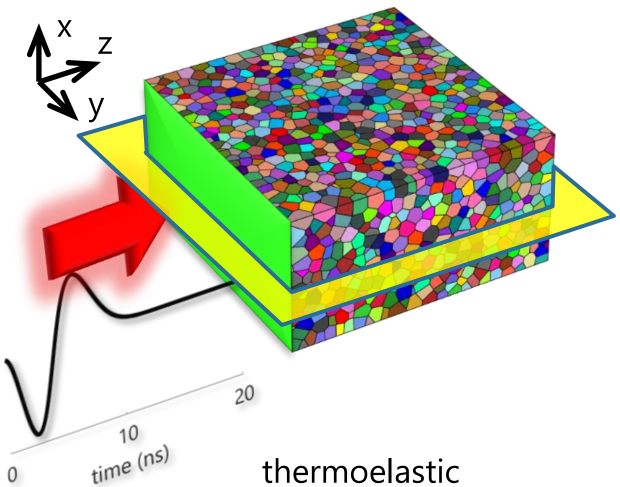
u_z (a.u.)



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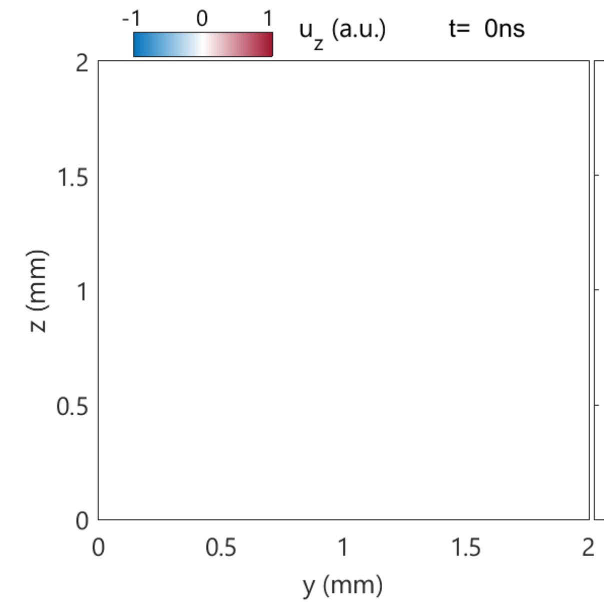
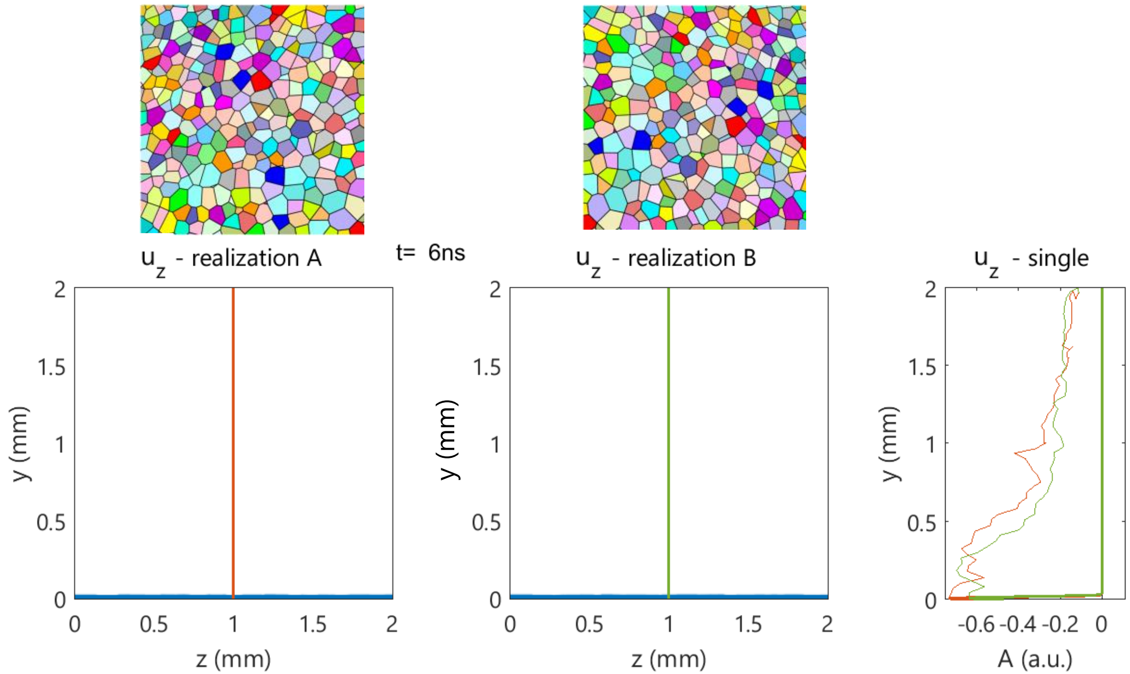


Time-domain FEM simulation of longitudinal-wave propagation

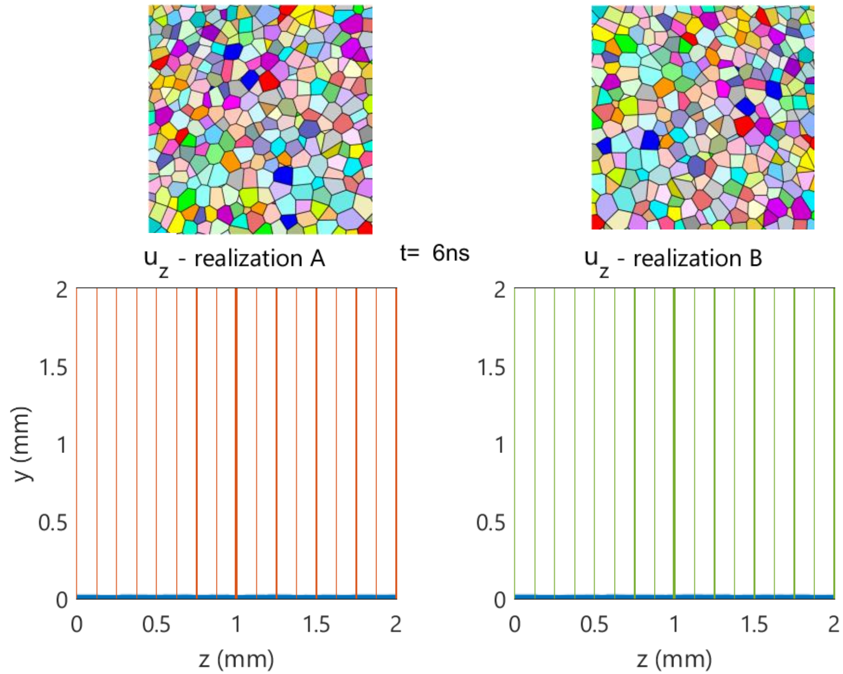
Coherent wave and attenuation



ballistic
wave

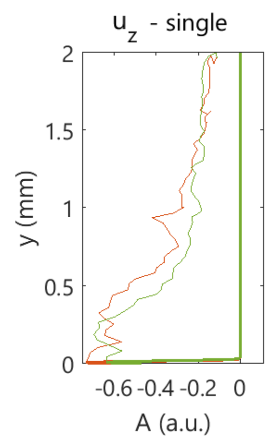
Same statistics (e.g. mean grain Ø),
different microscopic realization

Coherent wave and attenuation



Same statistics (e.g. mean grain Ø), different microscopic realization

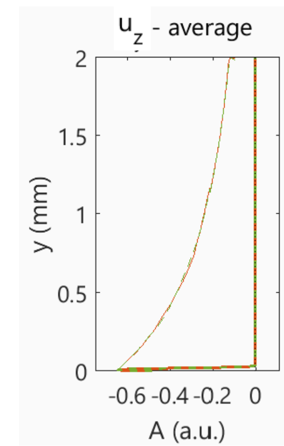
average in z-direction



ballistic wave

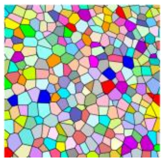
Attenuation

- Macroscopic
- Effective medium



'coherent wave'

Coherent wave and attenuation



Polycrystal

$\tilde{u}\,(x,\omega) = ?$

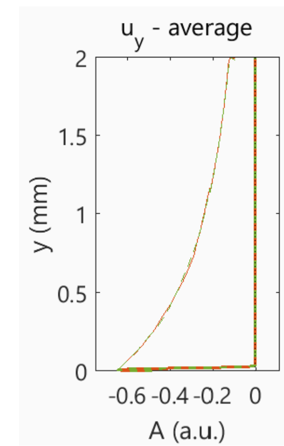
<u>Coherent wave</u> $\langle\tilde{u}\rangle(x,\omega) \propto e^{i(\tilde{k}x-\omega t)}$

$$\tilde{k} = \frac{\omega}{c(\omega)} + i\,\alpha(\omega)$$

Effective *homogeneous* medium with only parametrical description of the microstructure

<u>Attenuation</u>

- ☐ Macroscopic
- ☐ Effective medium



'coherent wave'

Scattering Regimes & Asymptotes

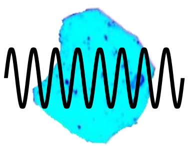
- Relation between attenuation $\alpha(\omega)$ and *microstructure* (grain size *d*)?

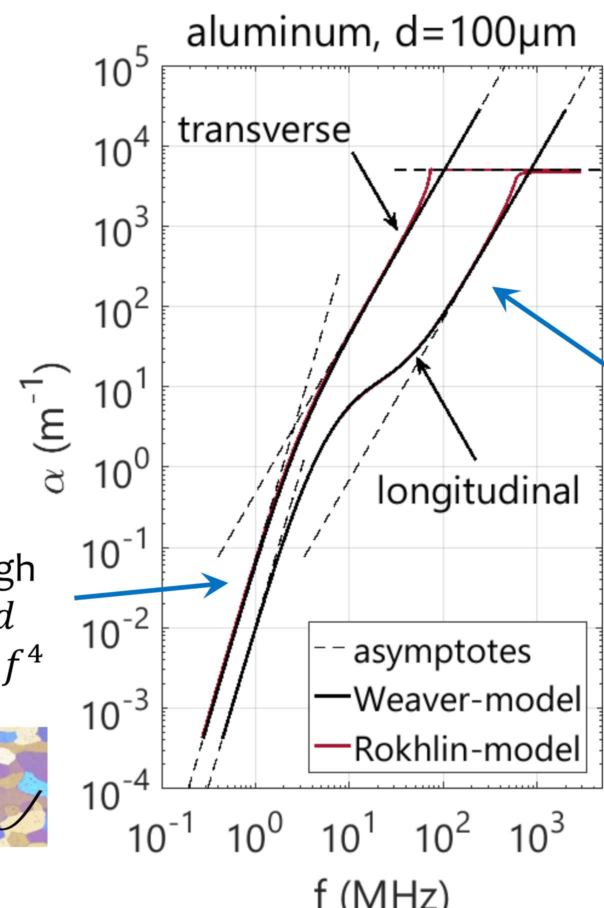
Analytical (attenuation) model

e.g.: Weaver's model

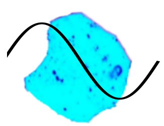
[Weaver, *J. Mech. Phys. Solids 38 (1990)*]

geometric
$\lambda \ll d$
$\alpha \propto \frac{1}{d}$

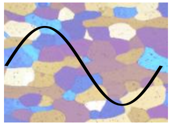




stochastic
$\lambda \approx d$
$\alpha \propto d f^2$



Rayleigh
$\lambda \gg d$
$\alpha \propto d^3 f^4$

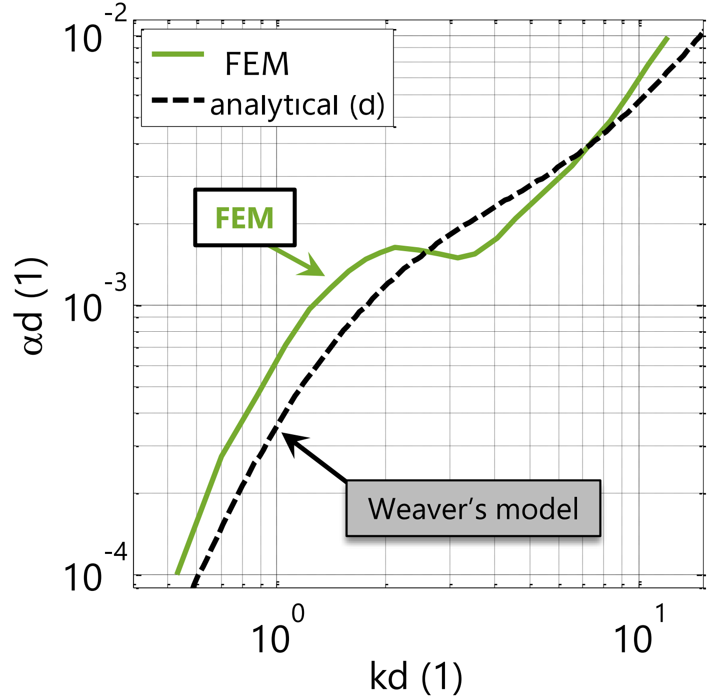


Simulation vs Experiment

[M. Ryzy et al., J. Acoust. Soc. Am. 143, 219 (2018)]

- Weak agreement with the model
  - Microstructure description?
    - Mean grain size *d*
      and assumed two-point correlation function (TPCF)

$$W(r) = e^{-r/d}$$



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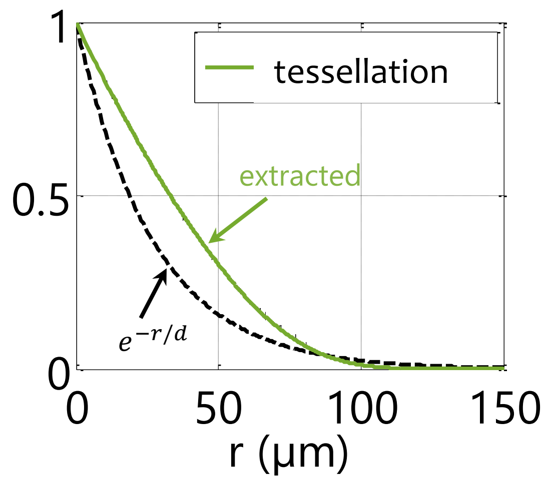
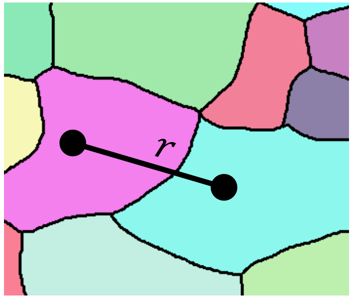
    - Not in agreement with the TPCF of the tessellation!



<u>Two-point correlation function:</u> the probability that two points separated by r are within the same grain



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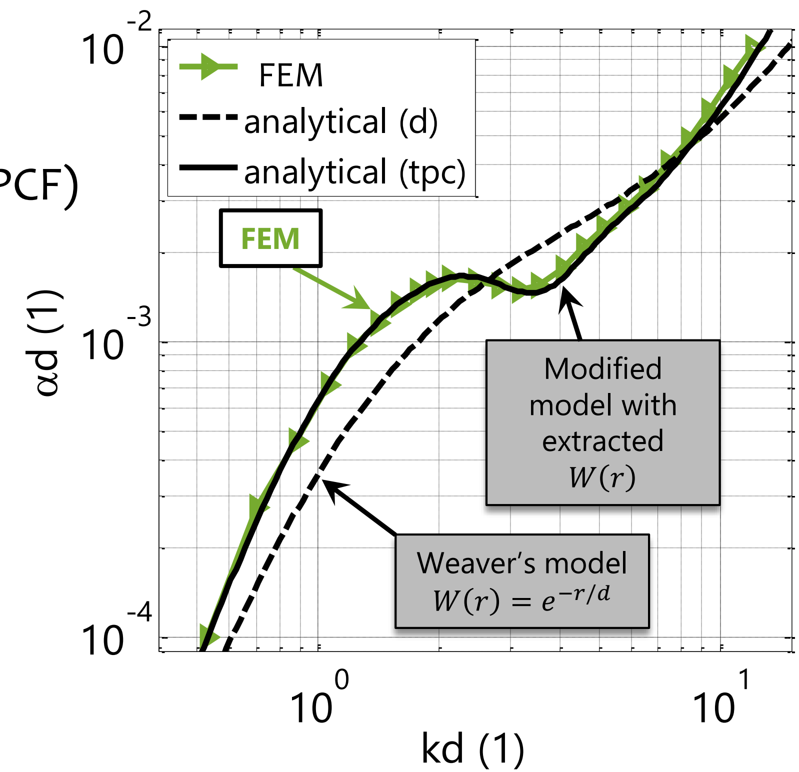
$$W(r) = e^{-r/d}$$

    - Not in agreement with the TPCF of the tessellation!
  - Modified Weaver's model with TPCF of the tessellation



TPCF as the crucial statistical parameter to describe the microstructure with respect to the scattering-induced attenuation!

Outline

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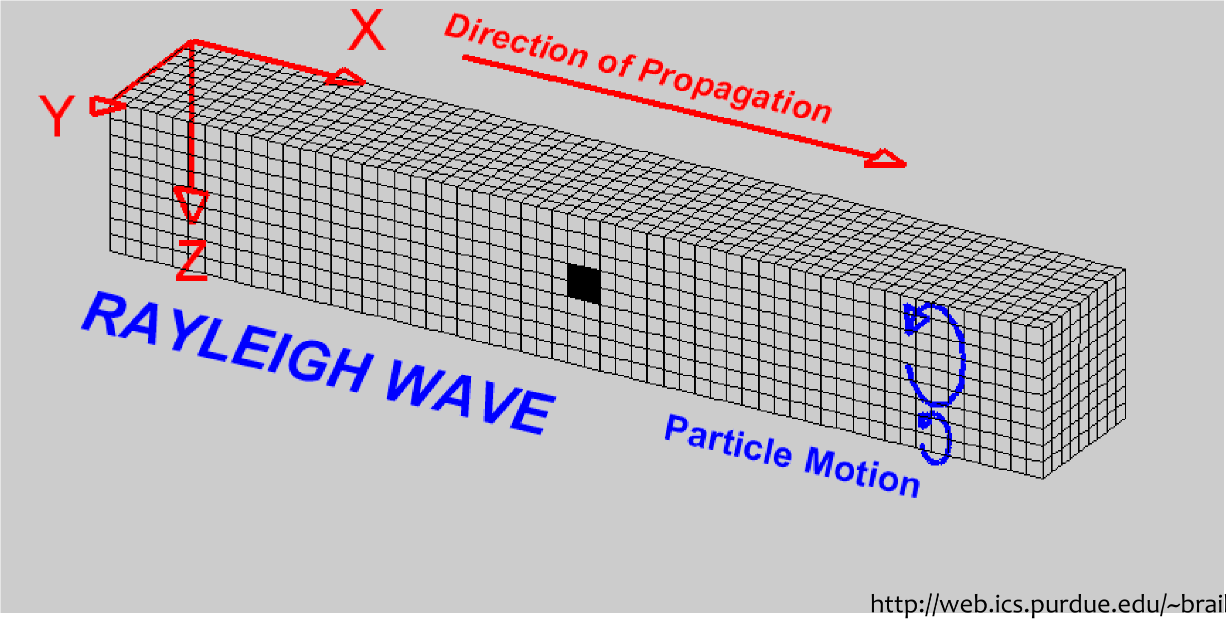
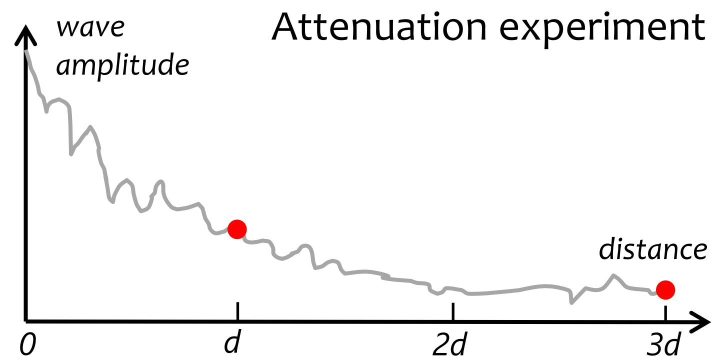
- **<u>Grain-Boundary Scattering of Surface Acoustic Waves</u>**

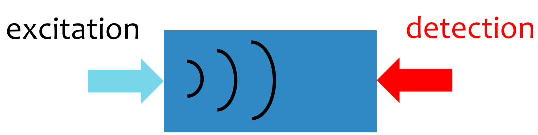


L. Braile, Purdue University
http://web.ics.purdue.edu/~braile/edumod/waves/WaveDemo.htm

Why SAW?

- Bulk-wave attenuation measurement at end points only



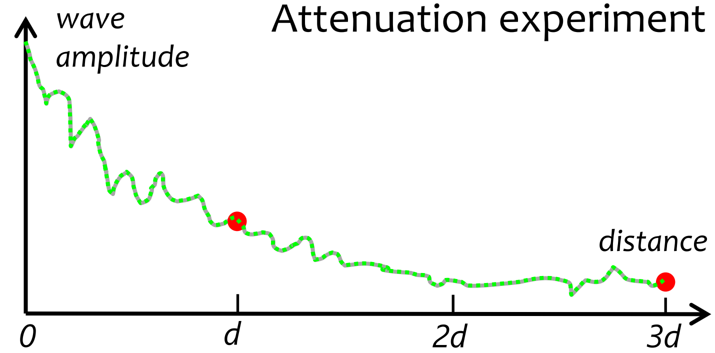


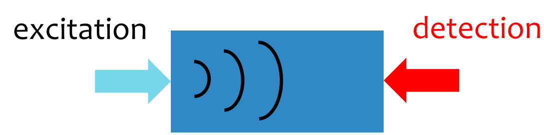
Longitudinal waves

Why SAW?

- Bulk-wave attenuation measurement at end points only
- SAW attenuation can be scanned!
  - Similar information as from simulation
  - Information from a near-surface layer
    - OK if homogeneous microstructure
    - … Allows to study surface properties if not
    - Penetration depth depends on wavelength

Attenuation experiment



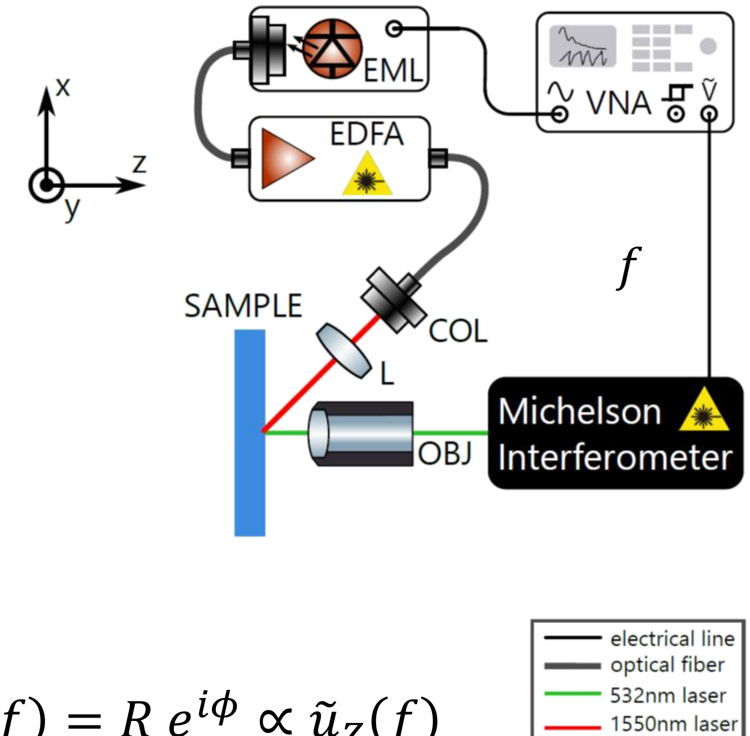


Longitudinal waves

Surface acoustic waves

Frequency-domain laser-ultrasonic setup

[M. Ryzy et al., AIP Advances 8 (2018)]



$$\tilde{V}(f) = R\, e^{i\phi} \propto \tilde{u}_Z(f)$$

Surface normal displacement

Excitation

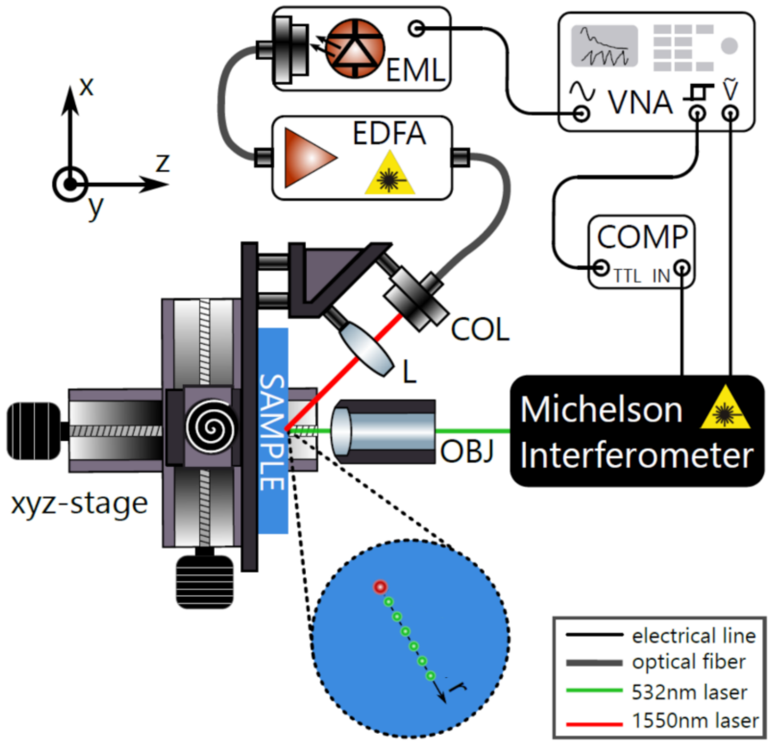
- Electro-absorption modulated Laser diode (EML), $\lambda = 1.55\mu m$ → P=0.2W
- Erbium doped fiber amplifier (EDFA) → $P \leq 1.2W$
- Point-source

Detection

- Michelson interferometer
- Vector network analyzer (phase sensitive detection)
- Point-probe ($\lambda = 532nm$)

Frequency-domain laser-ultrasonic setup

[M. Ryzy et al., AIP Advances 8 (2018)]



Get attenuation?

- Spatial scan
- Scan detection-point

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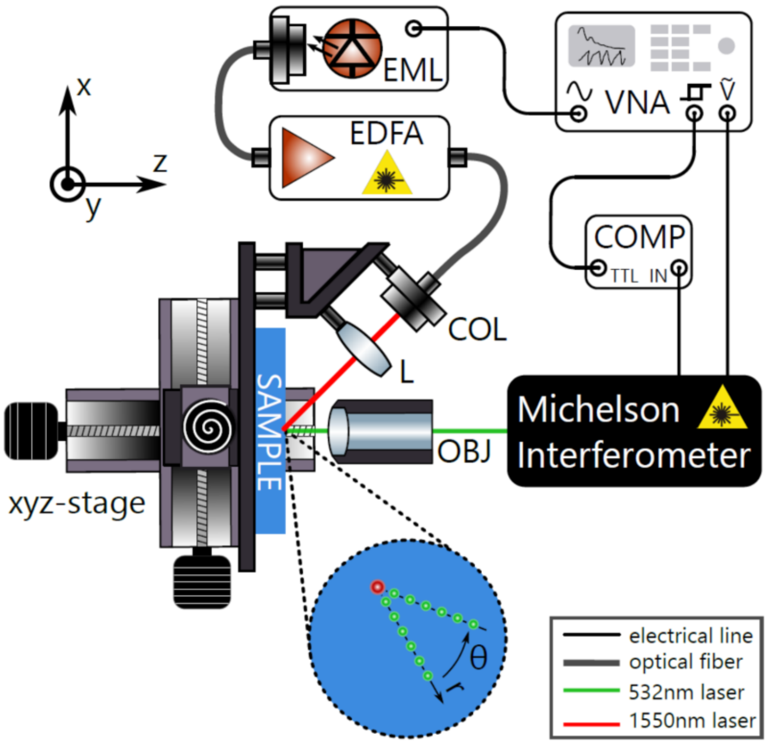


Get attenuation?

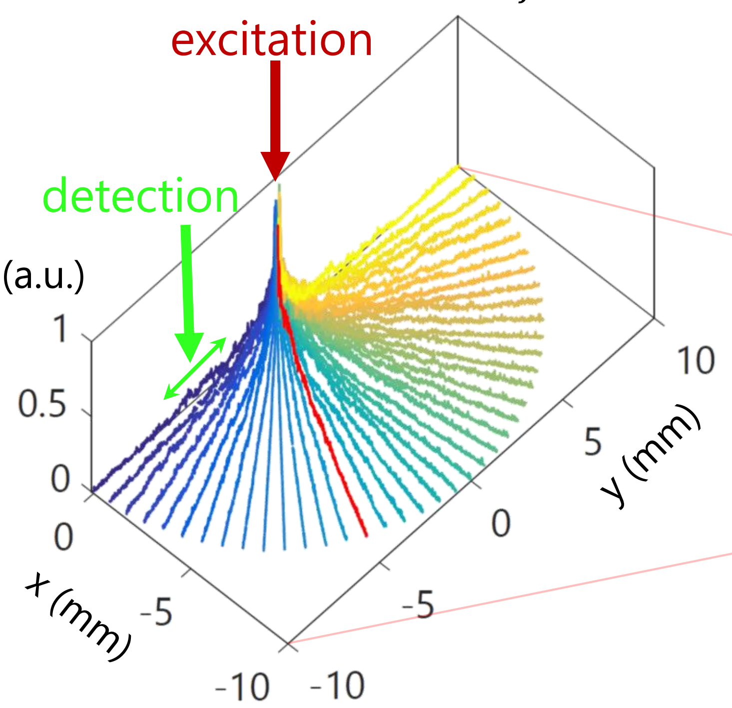
- Spatial scan
- Scan detection-point

Get *averaged* attenuation?

- Spatial averaging
- Scan radial lines

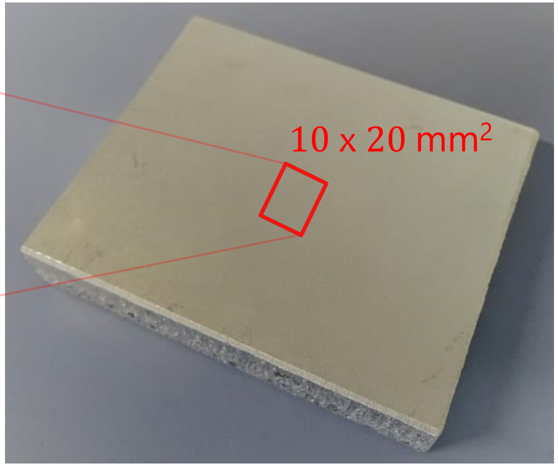
Frequency-domain experiment

[M. Ryzy et al., AIP Advances 8 (2018)]



Sample: Aluminum

≈ 80 x 80 x 12 mm^3



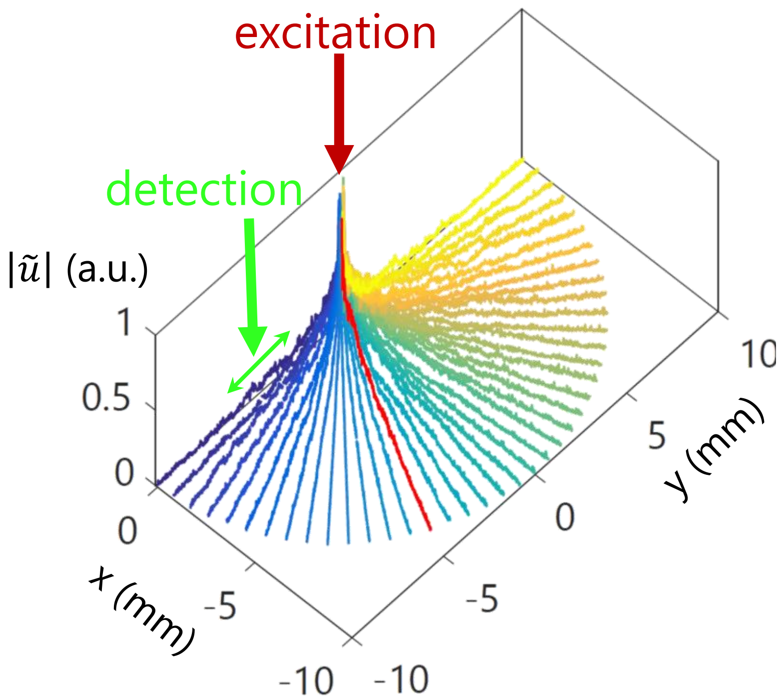
Frequency range: 10 … 130MHz ($\Delta f = 2\text{MHz}$)
Spatial resolution: 15µm

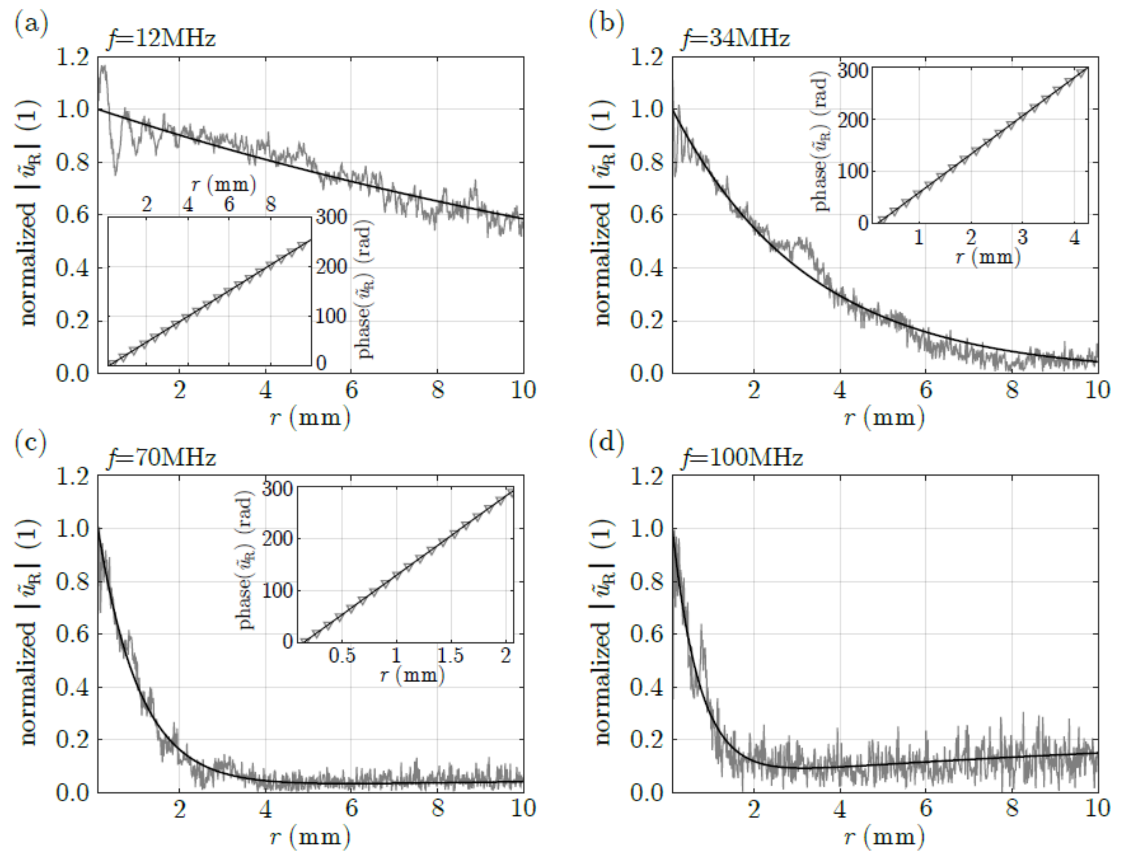
mean grain size

$d \approx 94.5\mu\text{m}$

Frequency-domain attenuation

[M. Ryzy et al., AIP Advances 8 (2018)]

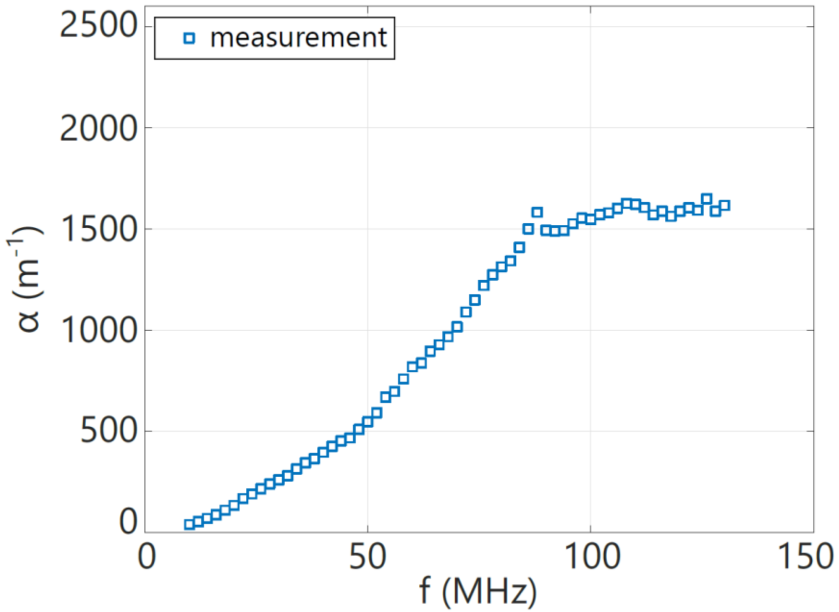




Experimental results

[M. Ryzy et al., AIP Advances 8 (2018)]

Results (linear)



Two scattering-regimes?

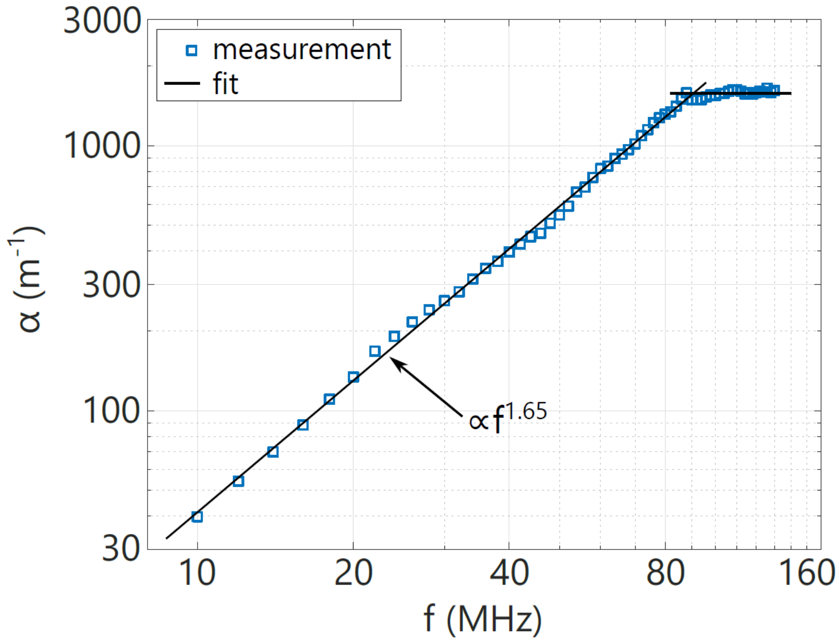
- Stochastic
- Geometric

... but the higher frequencies already strongly attenuated

Experimental results

[M. Ryzy et al., AIP Advances 8 (2018)]

Results (logarithmic)



$c = (2892.8 \pm 4.0)\mathrm{ms}^{-1}$

Two scattering-regimes?

- Stochastic
- Geometric

... but the higher frequencies already strongly attenuated

Simple theoretical model for SAW

[M. Ryzy et al., AIP Advances 8 (2018)]

- Assume that attenuation combined in a way similar to velocity
  - Simple model:
    - Modified Weaver's model
      → bulk-wave attenuation
    - Rayleigh equation for surface wave in complex wavenumbers

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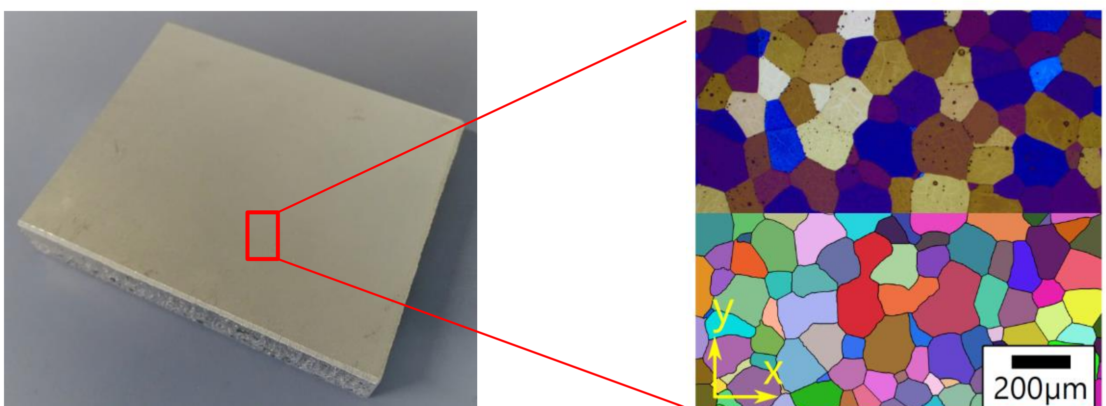
  - Simple model:
    - **Modified Weaver's model** → bulk-wave attenuation
    - Rayleigh equation for surface wave in complex wavenumbers

→ TPCF of the sample necessary!



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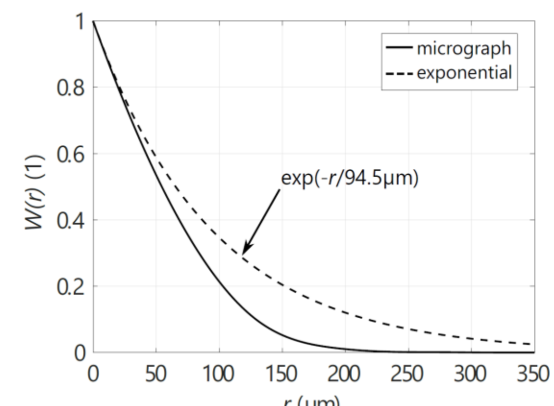
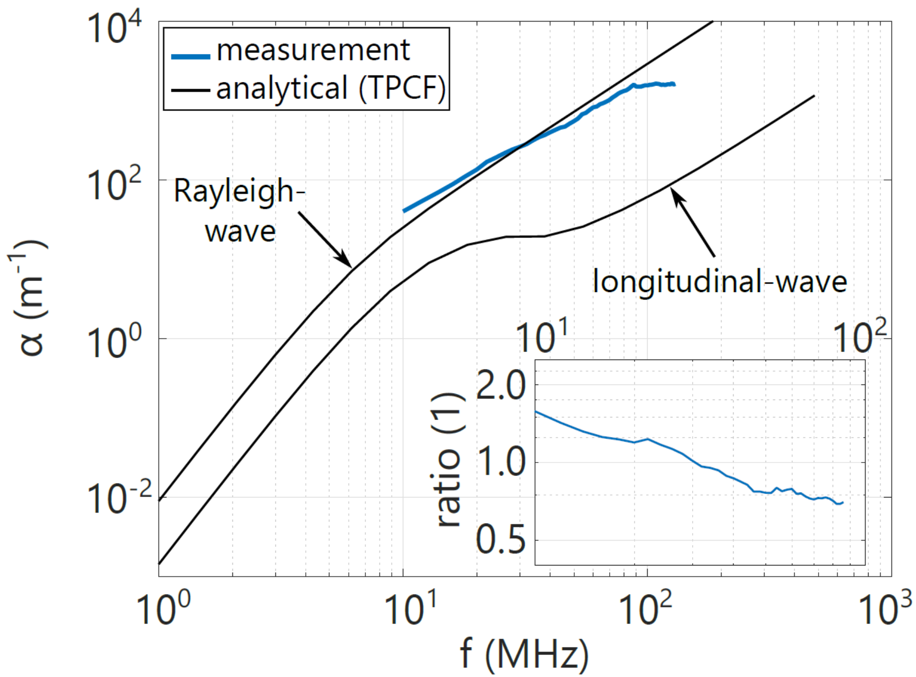


Experiment vs simple model

[M. Ryzy et al., AIP Advances 8 (2018)]

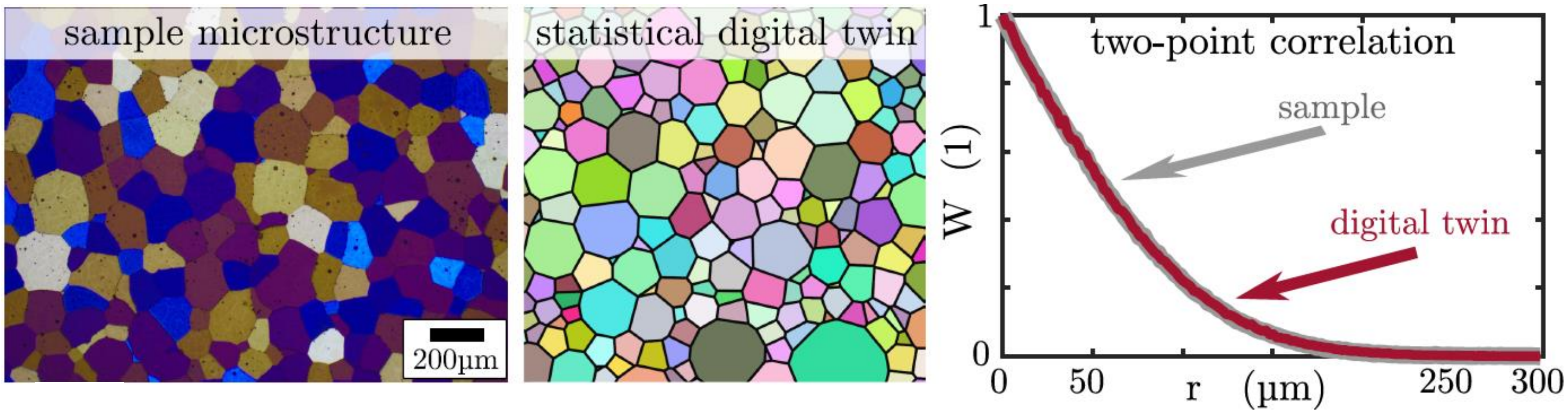
- Assume that attenuation combined in a way similar to velocity
  - Simple model:
    - Modified Weaver's model → bulk-wave attenuation
    - Rayleigh equation for surface wave in complex wavenumbers
- Slightly different power-law dependence in stochastic regime (1.65 vs. 2.0)
  - **Oversimplified analytical model or large experimental error?**



FEM simulation of SAW scattering

[T. Grabec et al., Ultrasonics 119 (2022)]

- FEM simulation directly comparable to the experiment? (in a statistical way)
  - Model of the sample → Statistical digital twin (Laguerre tessellation)



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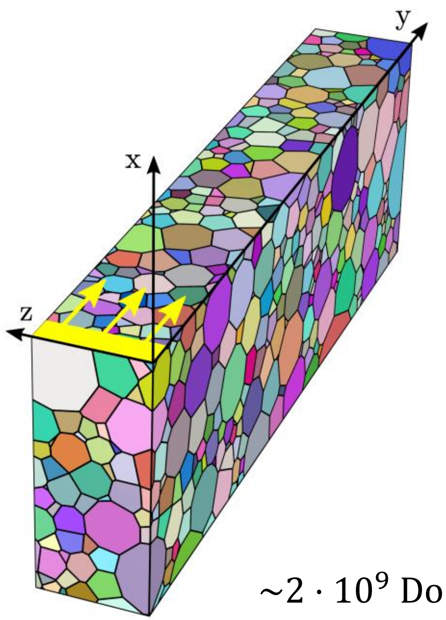
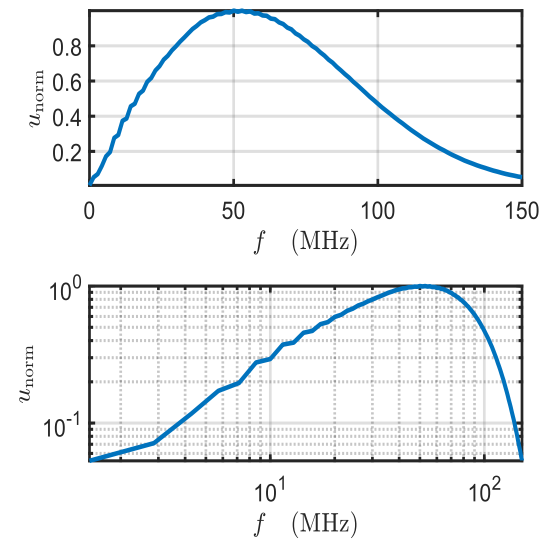
  - Broadband excitation:
    - Temporal and spatial gaussian profile



$\sim 2 \cdot 10^9$ DoF (60 runs)
elem . size 1.25 μm, time step 0.9 ns

Frequency profile of SAW in homogeneous domain:



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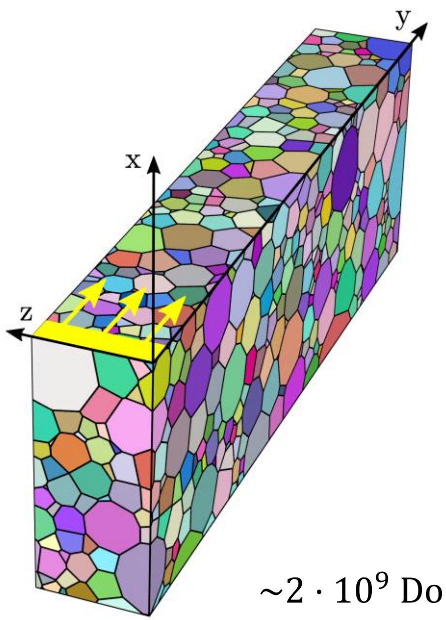

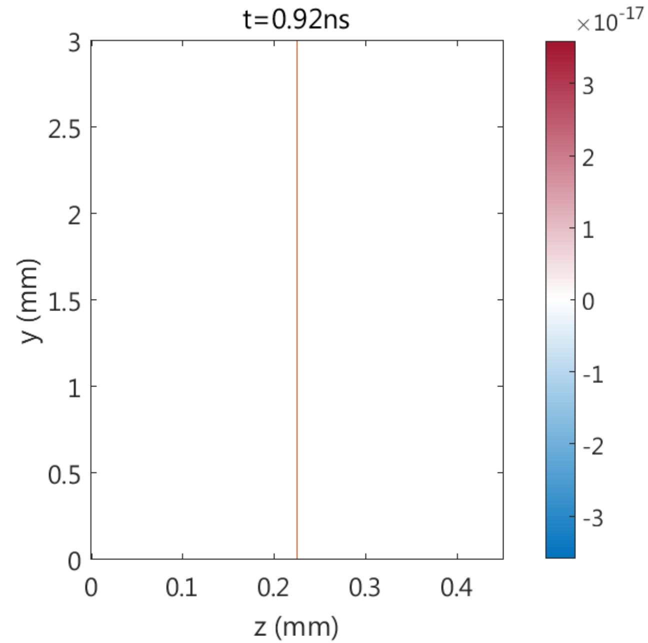

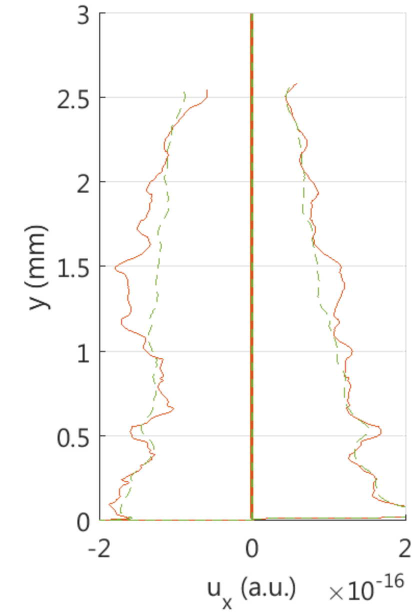

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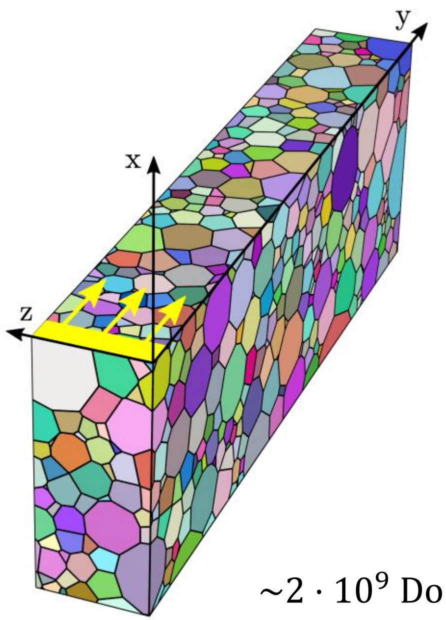
  - Model of the sample → Statistical digital twin
  - Broadband excitation → gaussian
  - Large number of repetitive runs to obtain the averaged response



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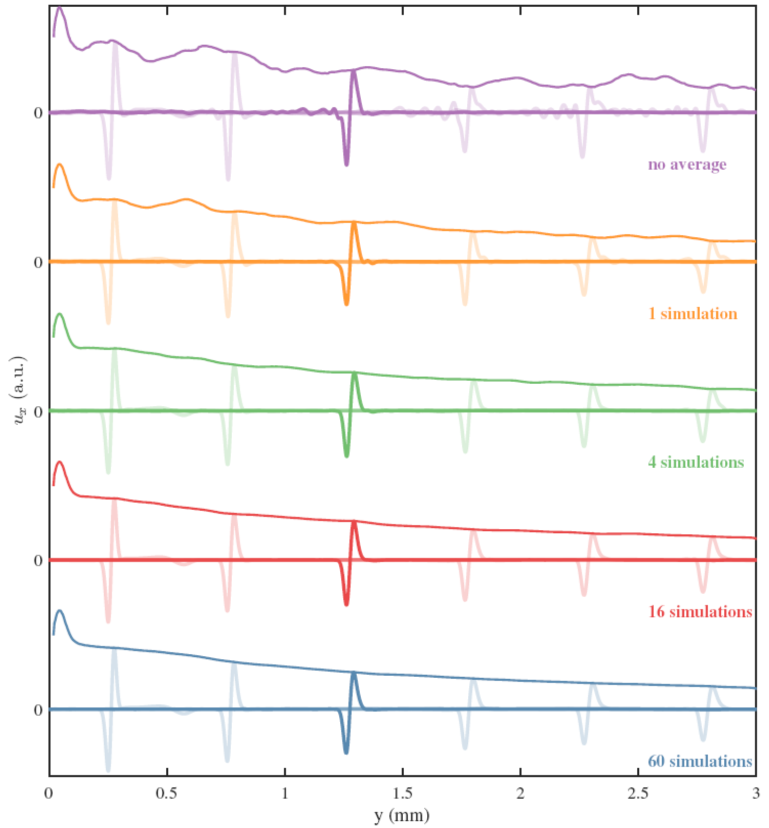
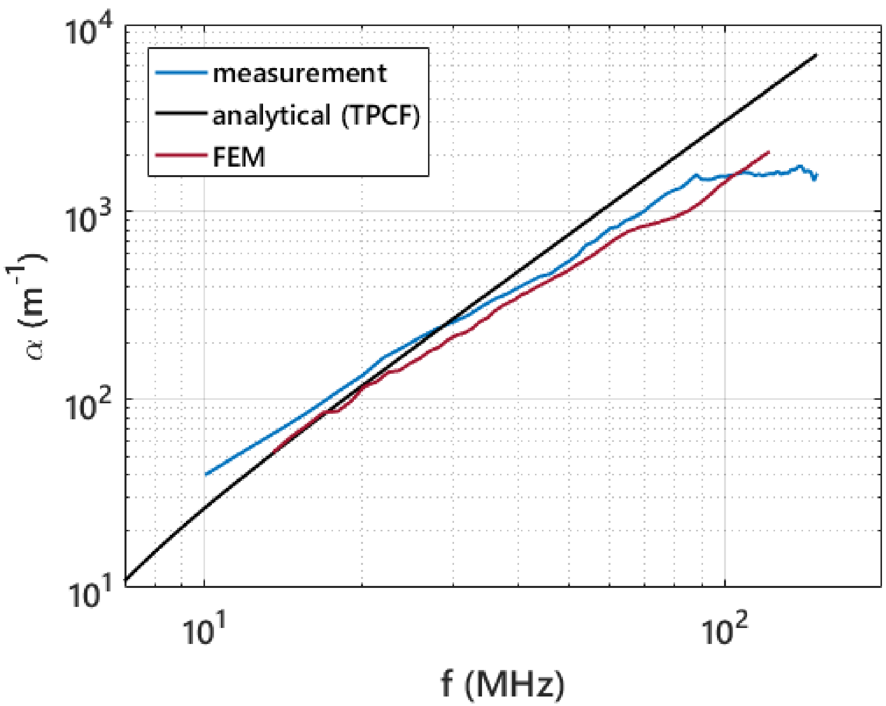


Simulation vs Experiment vs Model

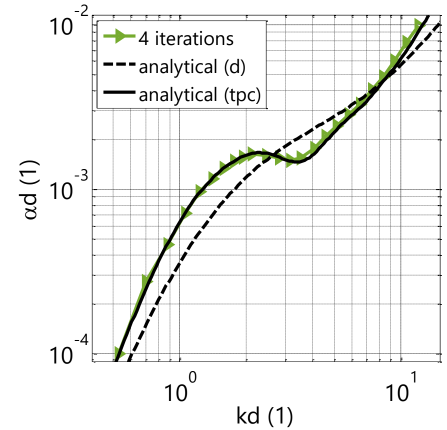
[T. Grabec et al., Ultrasonics 119 (2022)]

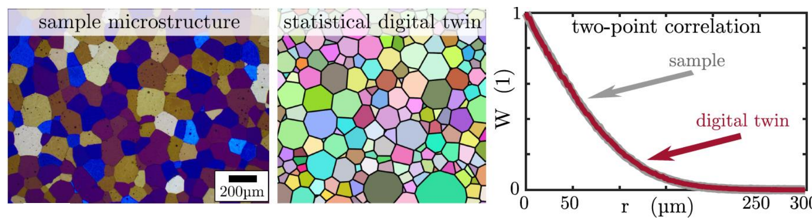
- Simulation in great agreement with the experiment!
  → better than with the model
  - Both experiment and FEM suggest different slope (power-law exponent) than for bulk waves
    → more complex analytical description necessary!
  - Apparent geometric region in experiment not shown by FEM
    → probably a result of large error in experiment at higher frequencies



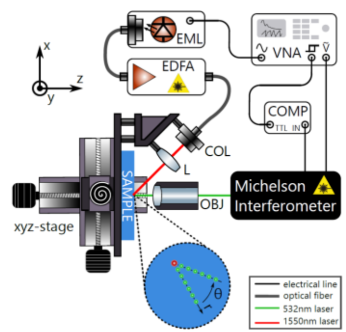
Conclusion

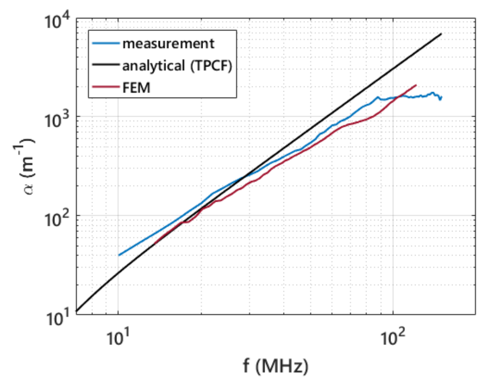
- Analysis of L-wave attenuation:
  - Importance of two-point correlation function (TPCF) for microstructure description: Excellent fit of TPCF-corrected analytical model with FEM simulation





- SAW attenuation:
  - Simple model proposed – combining Weaver's model with Rayleigh equation in complex wavenumbers
  - Frequency-dependent attenuation measured experimentally using laser-ultrasonic setup
  - FEM simulations on sample-mimicking tessellation
  - Excellent agreement between simulation and experiment





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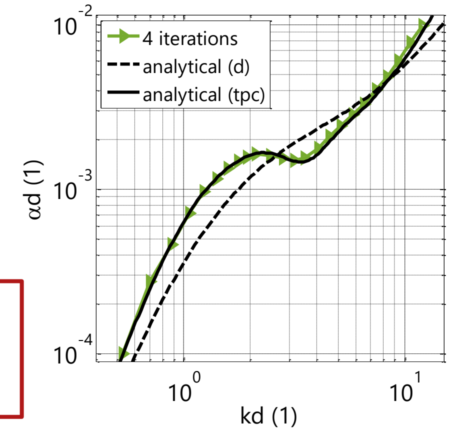

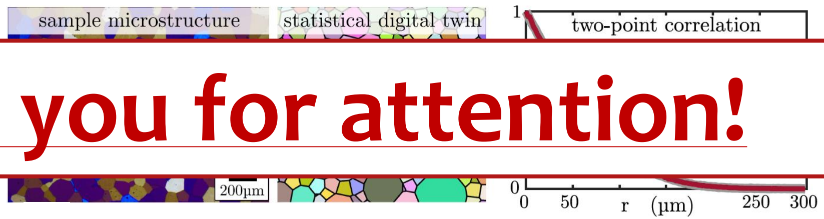

Thank you for attention!

- SAW att
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