Measurement and calculation of sound velocities of steel during recrystallisation

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LUS4Metals, 22.05.2024, Stockholm

1 RECENDT RESEARCH CENTER NON DESTRUCTIVE TESTING

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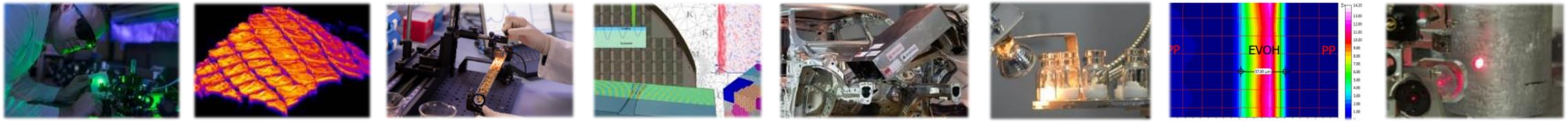
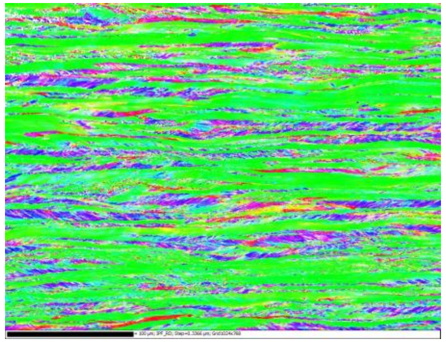


Recrystallization

Cold rolled steel sheets

- Shape of grains: Elongated grains → Equiaxed grains
- Orientation of grains: Rolling texture → Recrystallized texture

0% REXX



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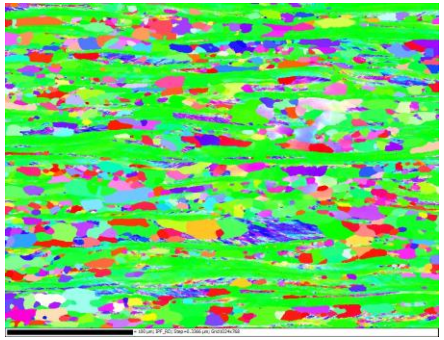
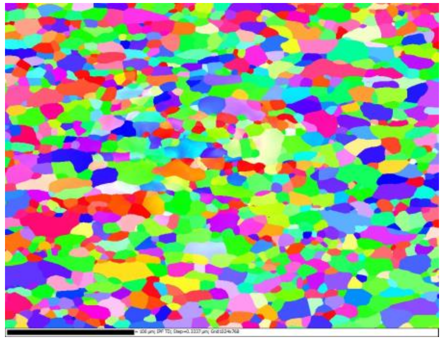
50% REXX at 640°C



→

100% REXX at 700°C



Technical importance: Forming behavior

Engler and Randle, V., 2008, *Introduction to Texture Analysis : Macrotexture, Microtexture, and Orientation Mapping*.

Why LUS for Recrystallization?

- State of the art methods: direct, ex-situ, slow

  Micrographs, Electron back scatter diffraction (EBSD), Microhardness, …

- Laser Ultrasound: in-situ, fast, indirect

  Sound velocities, attenuation

Electric arc furnace and scrap metal recycling

- Tramp elements in scrap metal
- Many characterization measurements

greentec steel

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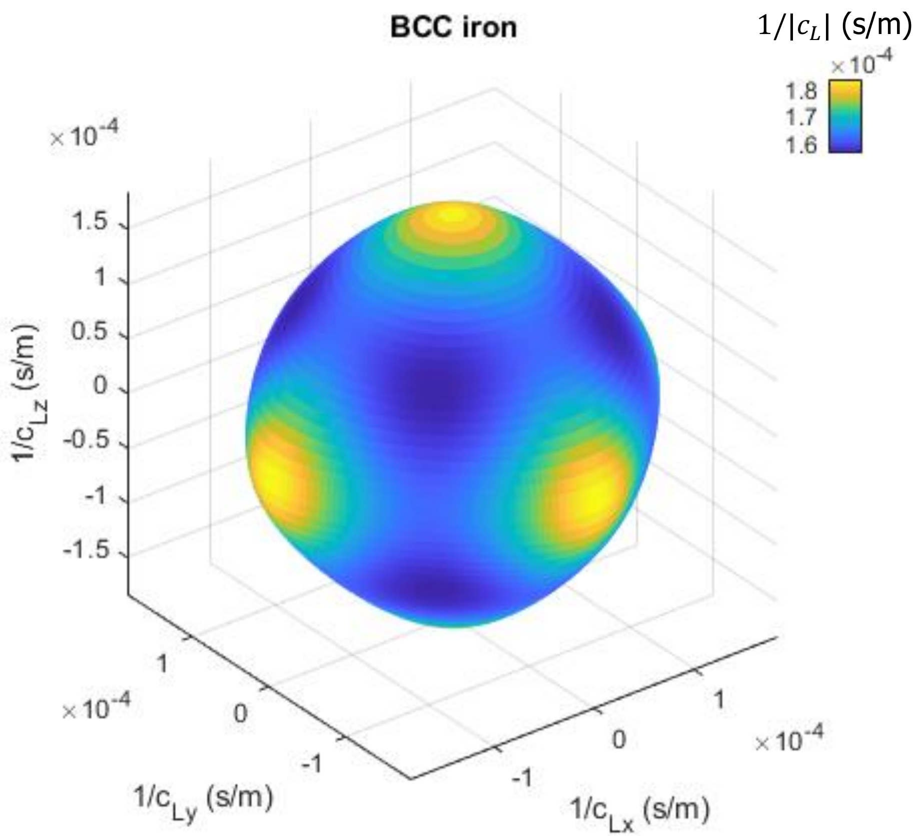
-30% CO_2 by 2027

Sound velocity in cold rolled steel

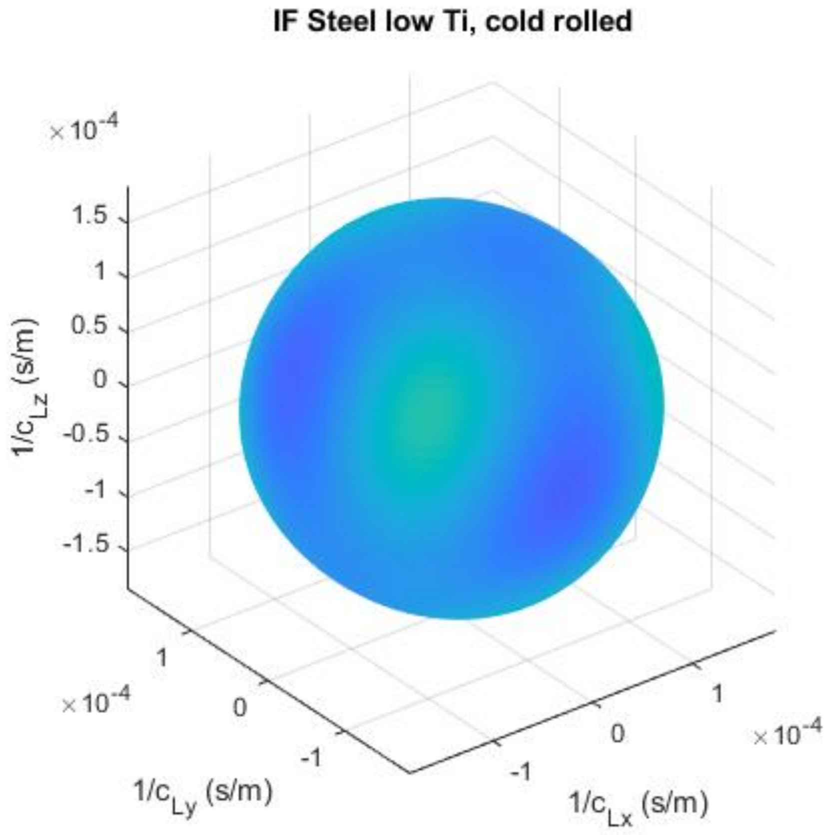
- Single crystal iron

  Directional dependence of sound velocities



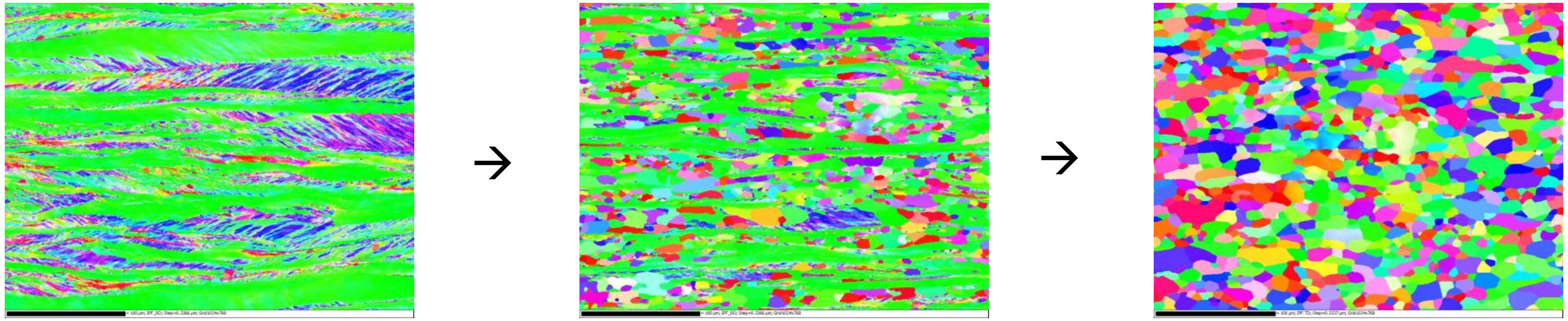
- Polycrystalline iron with texture

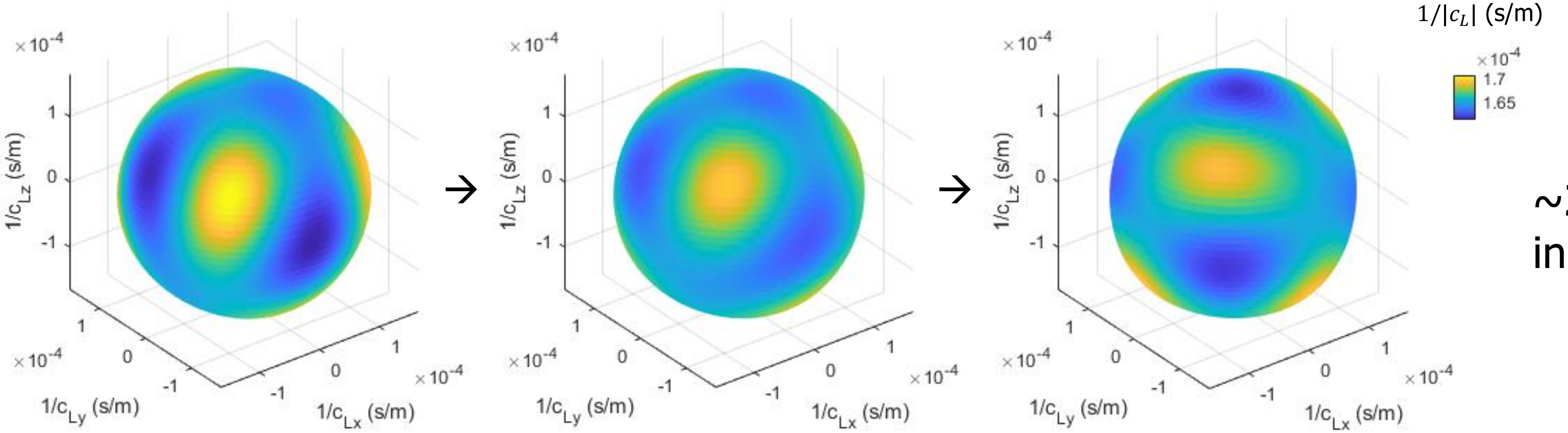
  Non uniform orientation distribution of grains



Change of grain orientation distribution

0% at 600°C → 50% at 640°C → 100% at 700°C





~2% change of c_L in normal direction

Calculating sound velocity

- Homogenized elastic stiffness tensor:

rotated single crystal stiffness tensor ($C(T)$ from *Dever, D. J., 1972)*

$$\underbrace{C(\varphi_1, \Phi, \varphi_2)}$$

Calculating sound velocity

- Homogenized elastic stiffness tensor:

rotated single crystal stiffness tensor ($C(T)$ from *Dever, D. J., 1972)*

$$\underbrace{\mathrm{f}(\varphi_1,\Phi,\varphi_2)}_{\text{orientation density (from EBSD)}}\ \overbrace{C(\varphi_1,\Phi,\varphi_2)}^{\text{rotated single crystal stiffness tensor}}$$

orientation density (from EBSD)

Calculating sound velocity

- Homogenized elastic stiffness tensor:

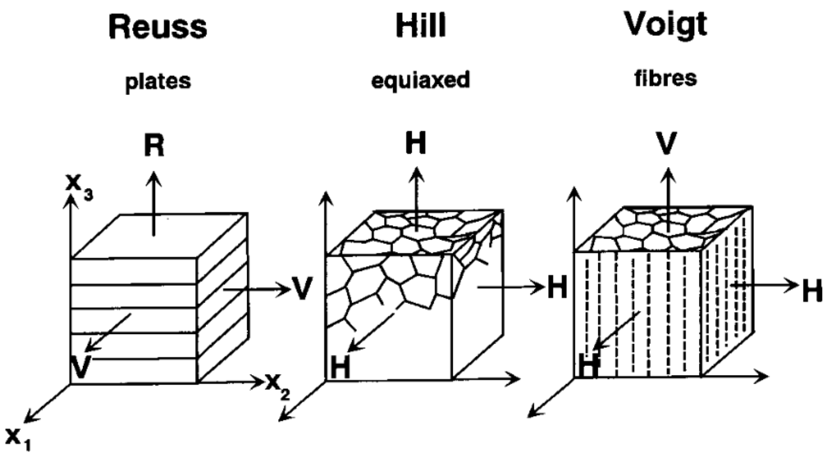
$$C_{Voigt} = \frac{4}{\pi^2} \iiint_0^{\frac{\pi}{2}} \mathrm{f}(\varphi_1, \Phi, \varphi_2)\, C(\varphi_1, \Phi, \varphi_2) \sin(\Phi)\, d\varphi_1 d\Phi d\varphi_2$$

Integral over Euler Space (all Orientations)

Calculating sound velocity

- Homogenized elastic stiffness tensor:

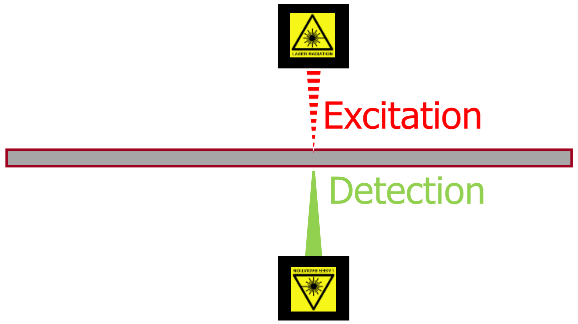
$$C_{Voigt} = \frac{4}{\pi^2} \iiint_0^{\frac{\pi}{2}} \mathrm{f}(\varphi_1, \Phi, \varphi_2)\, C(\varphi_1, \Phi, \varphi_2) \sin(\Phi)\, d\varphi_1 d\Phi d\varphi_2$$



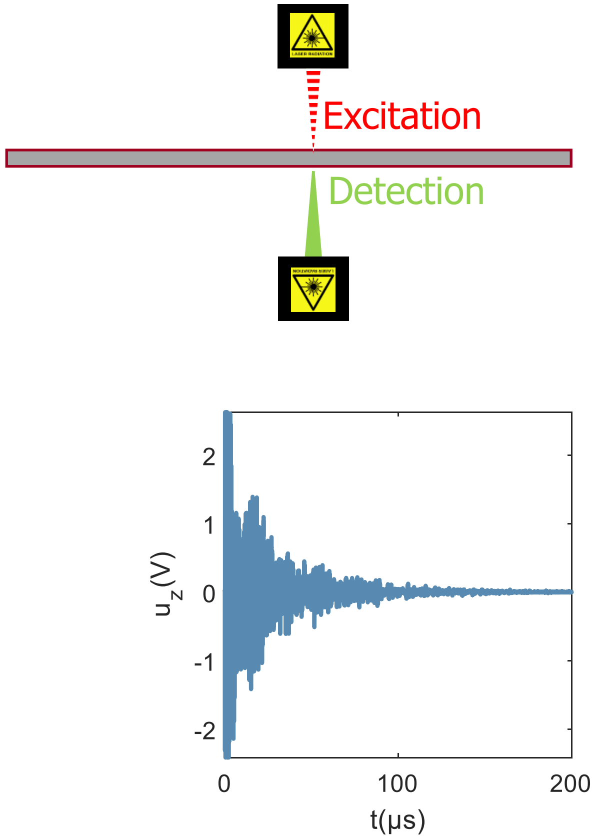
Bunge et al., 2000, "Elastic Properties of Polycrystals - Influence of Texture and Stereology," J. Mech. Phys. Solids, **48**(1), pp. 29–66.

- C_{Voigt} and C_{Reuss}: Theoretical limits
- Combinations: $C_{VR} = w\, C_V + (1 - w) C_R$
- solve wave equations ➔ sound velocities

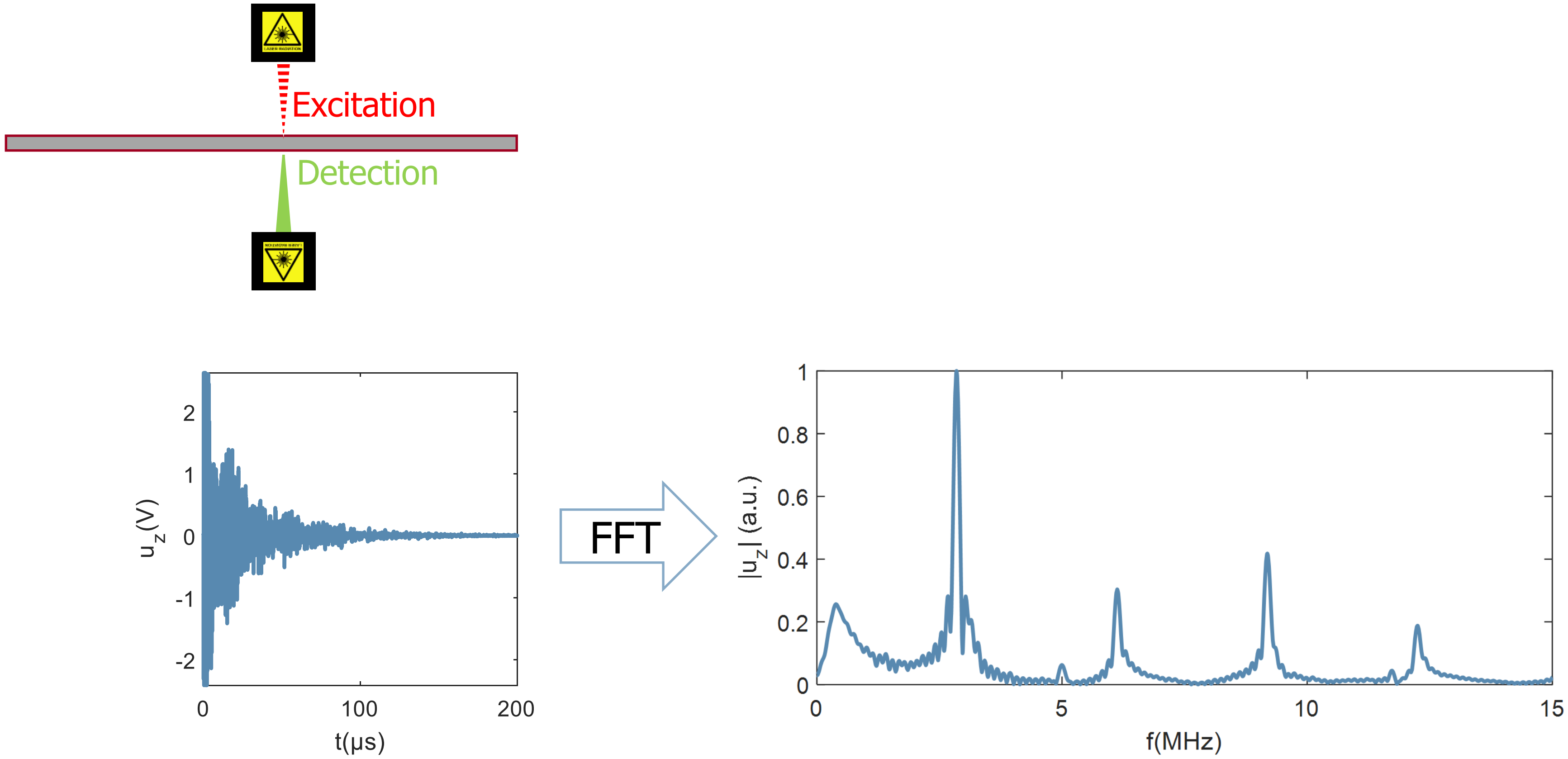
Measurement of plate resonances



Measurement of plate resonances

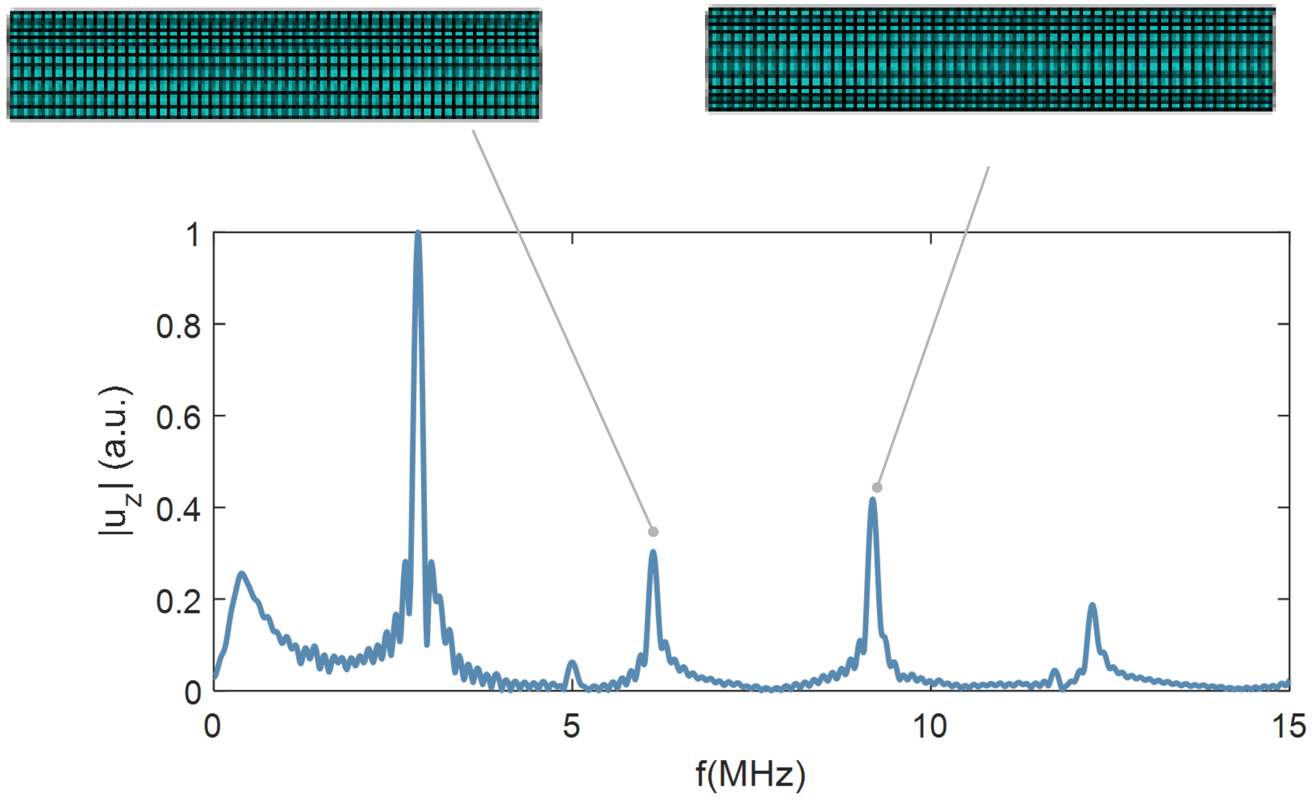


Measurement of plate resonances



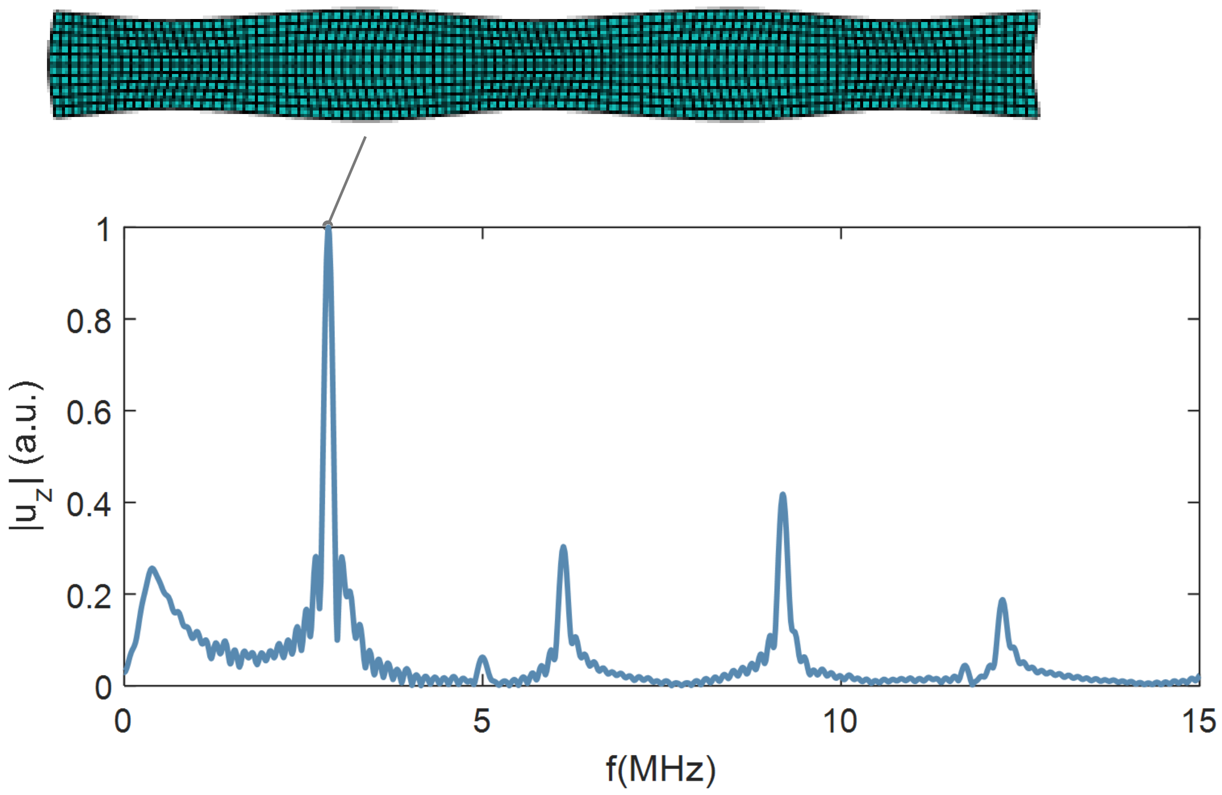
Measurement of plate resonances

thickness-resonances: standing plane waves at $f_L = n\frac{c_L}{2h}$



Measurement of plate resonances

Largest: Zero-Group-Velocity resonance



Measurement in thermal simulator

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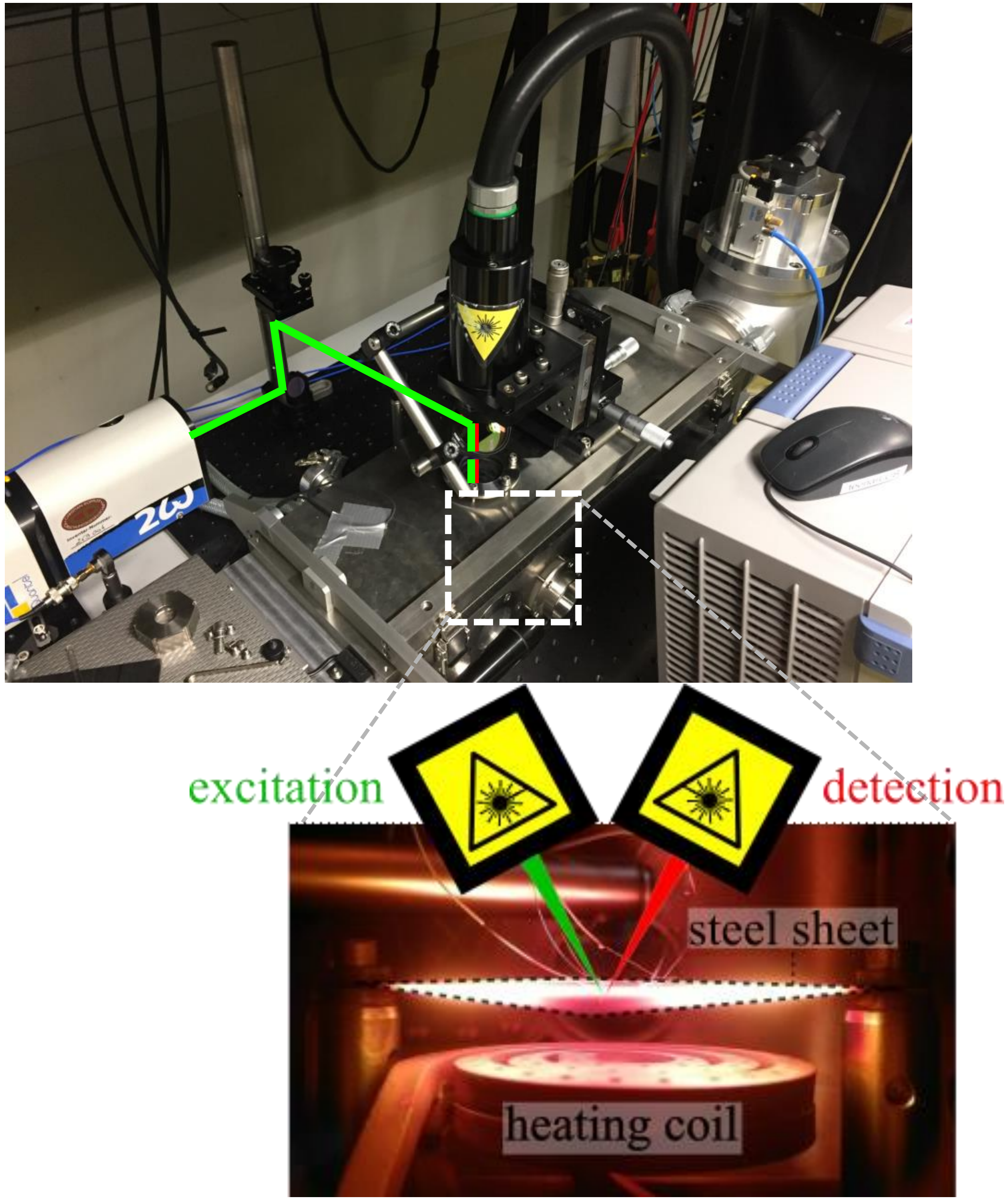
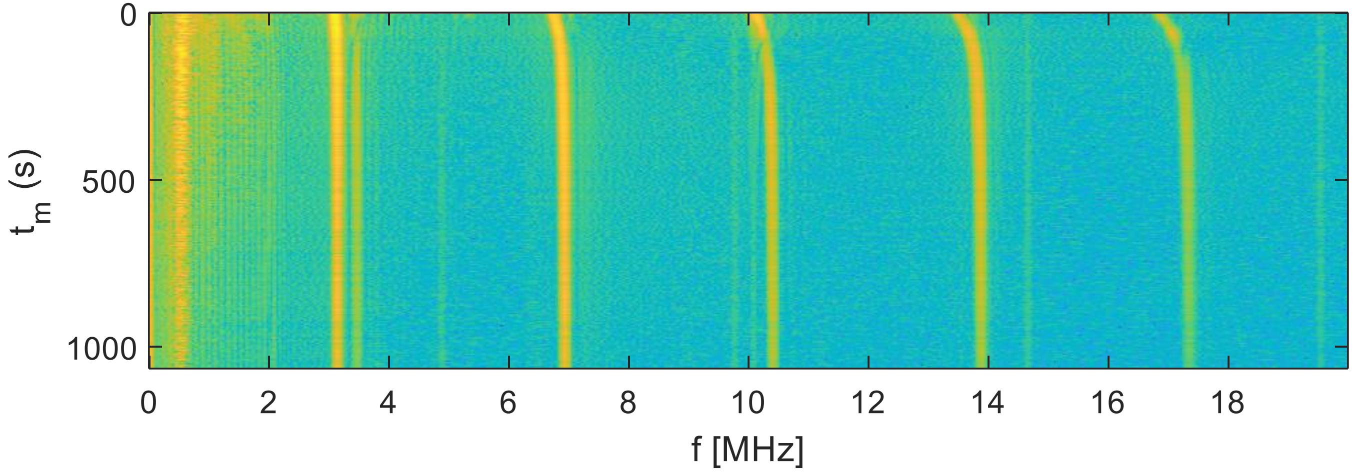
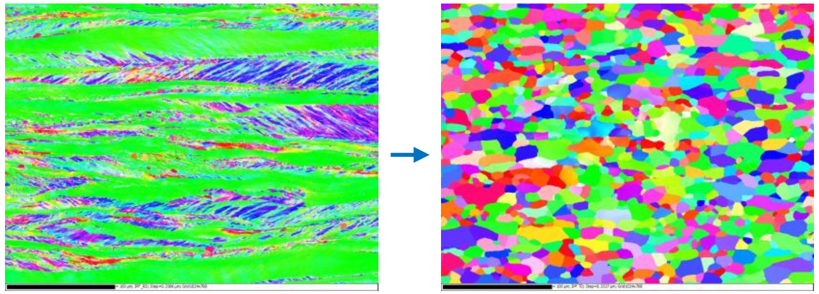
- Linseis Dilatometer, LUS coupled through windows
- Detection: TECNAR PDL (1064nm, 10Hz, 30mJ)
- Generation: Quantel Q-Smart 850 (532nm, 10Hz, 100mJ)

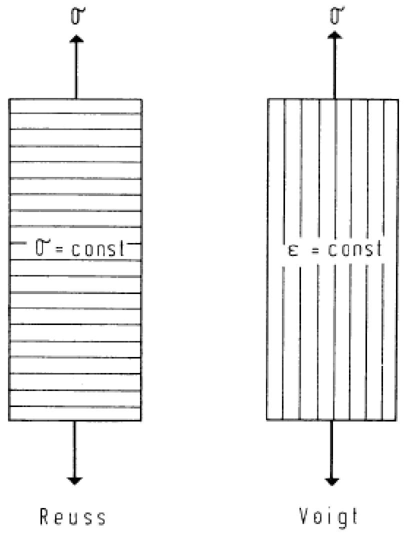


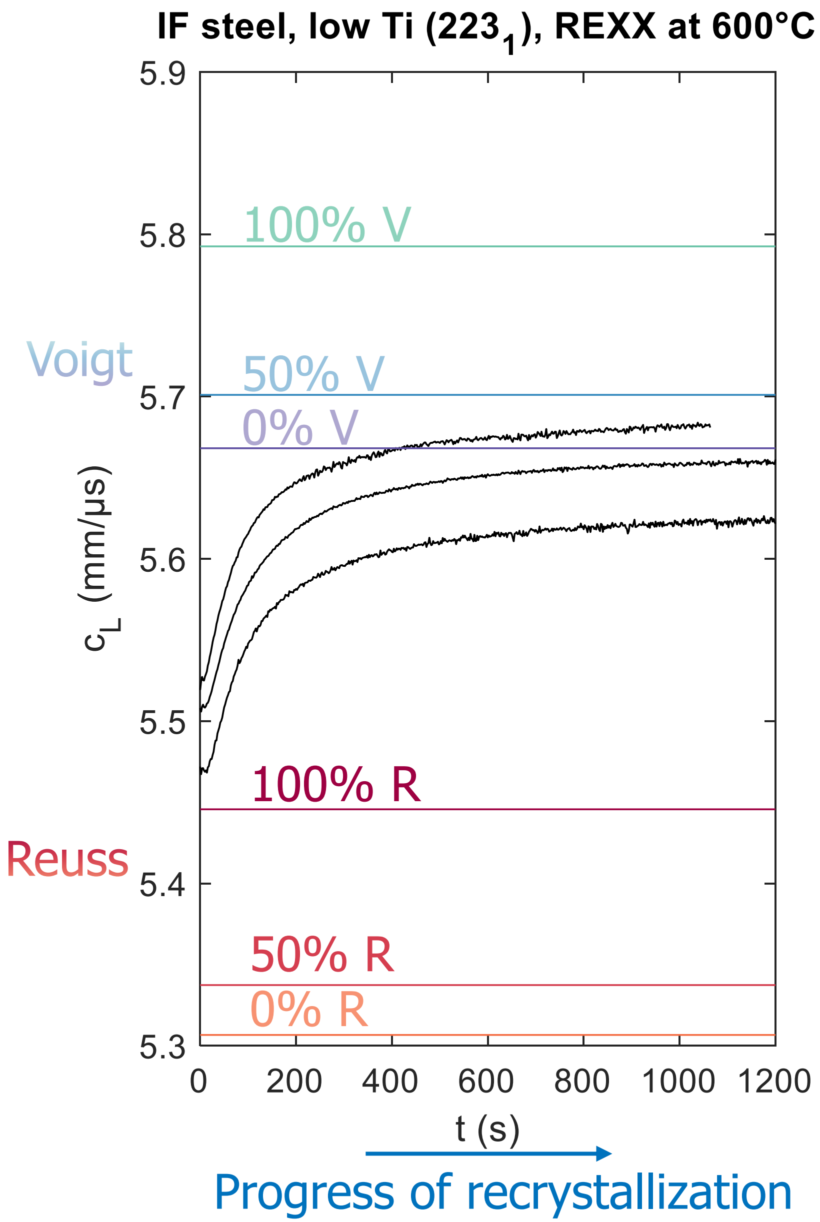
In situ during recrystallisation at 600°C:



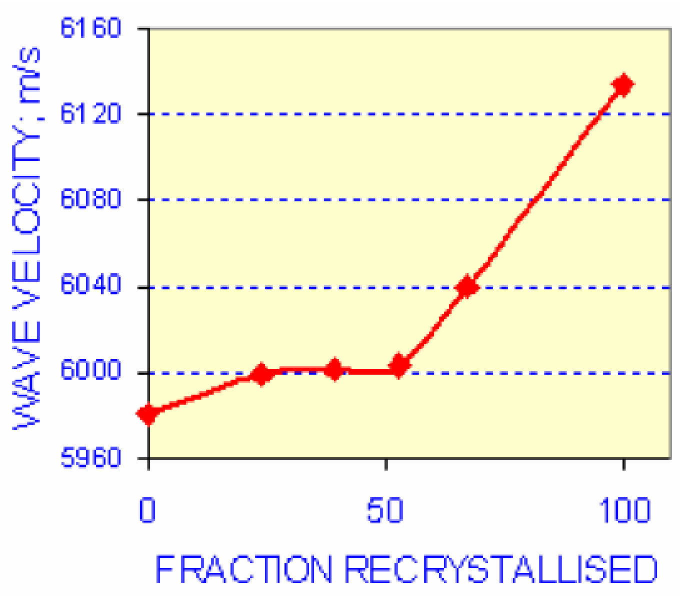
Calculated vs. measured c_L



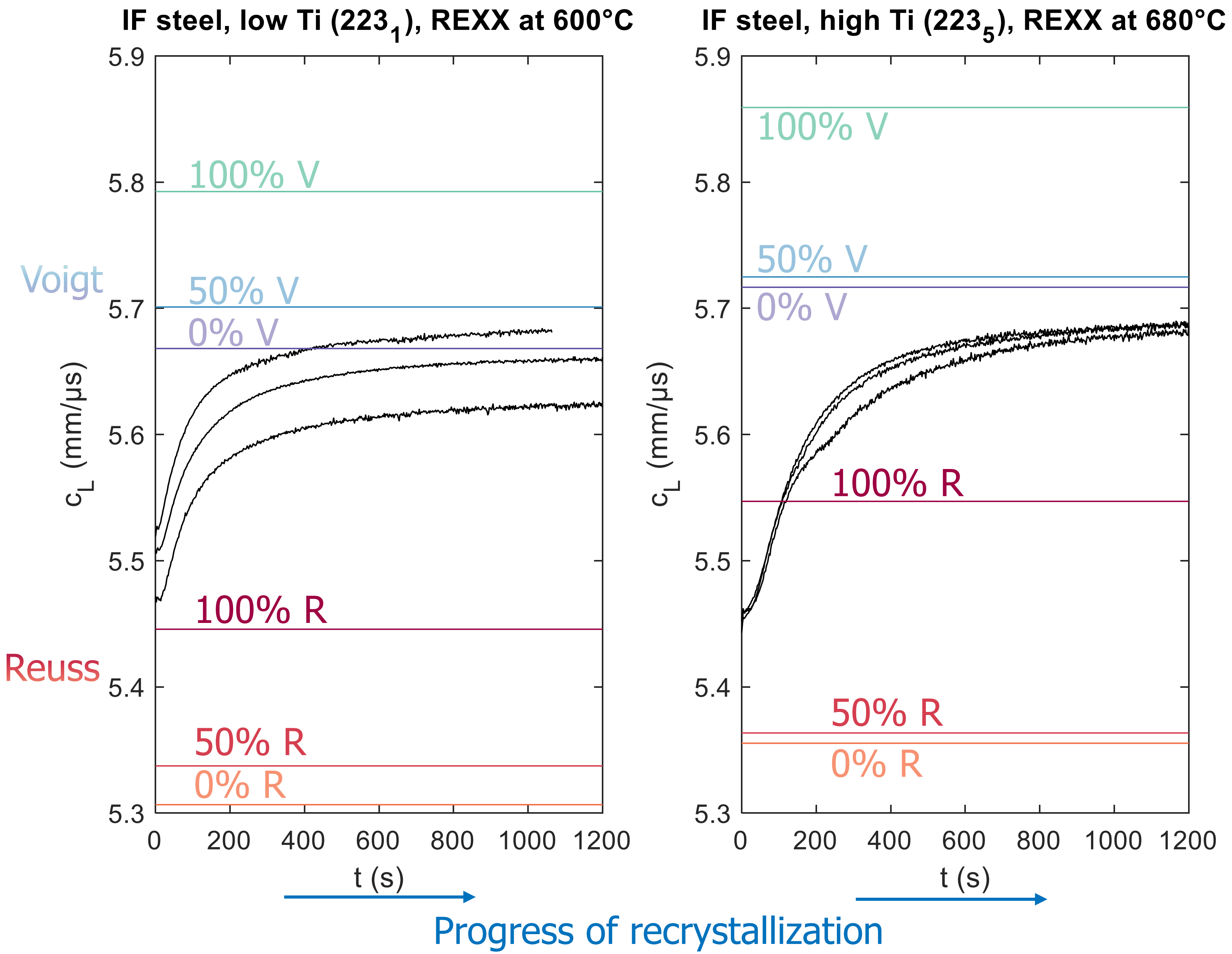




Calculated vs. measured c_L



Hutchinson et al., 2008, "Application of Laser Ultrasonics to Studies of Recrystallisation and Grain Growth in Metals," Technology, pp. 2–7.

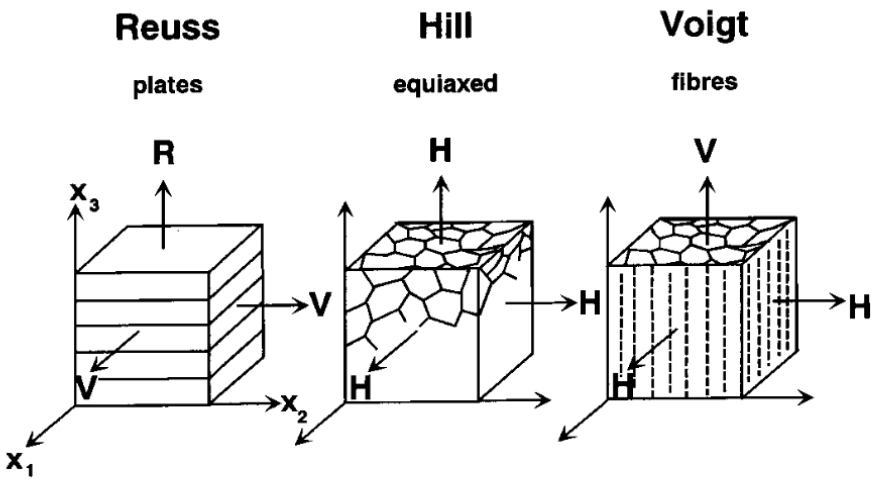


Calculated vs. measured c_L

Combine Voigt and Reuss:

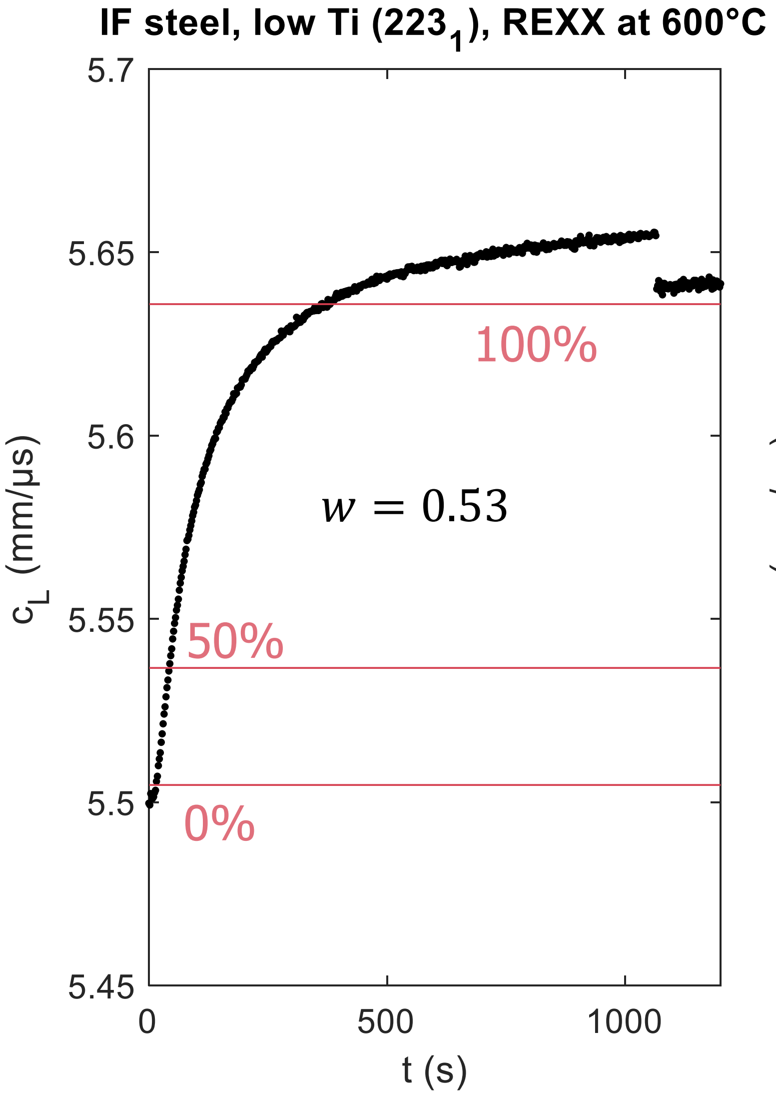
$$C_{VR} = w\, C_V + (1 - w) C_R$$

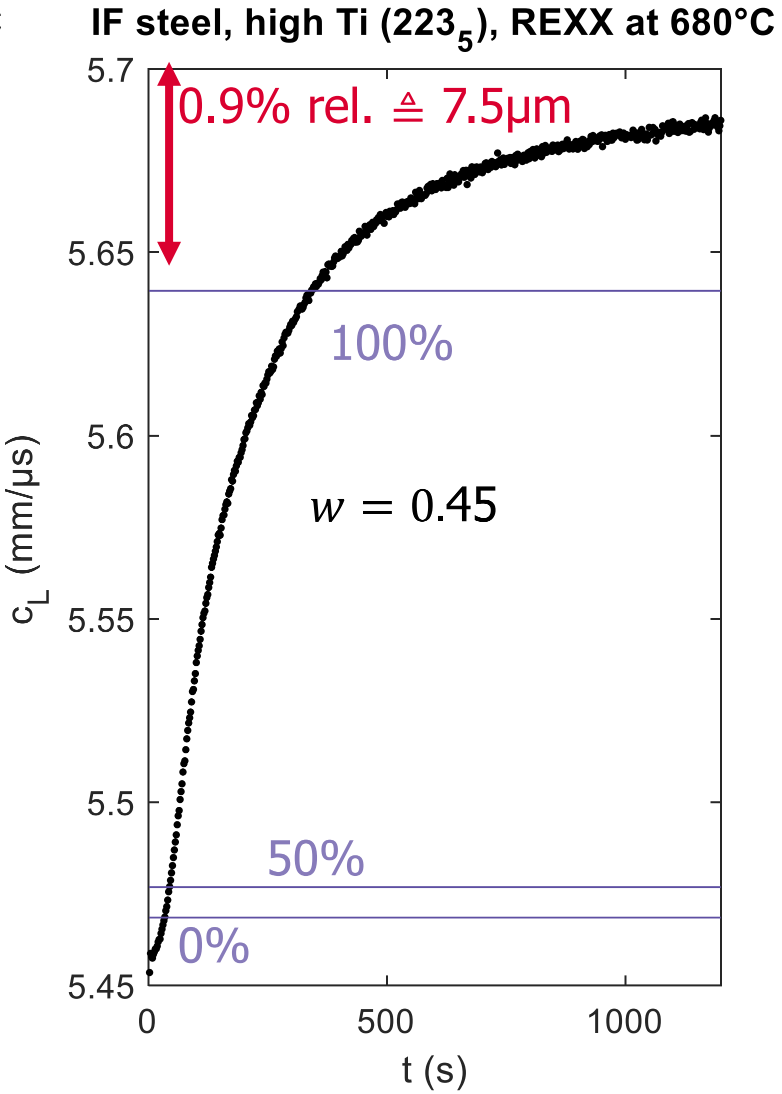
Reuss → Voigt? Change of w?



Bunge et al., 2000, "Elastic Properties of Polycrystals - Influence of Texture and Stereology," J. Mech. Phys. Solids, **48**(1), pp. 29–66.

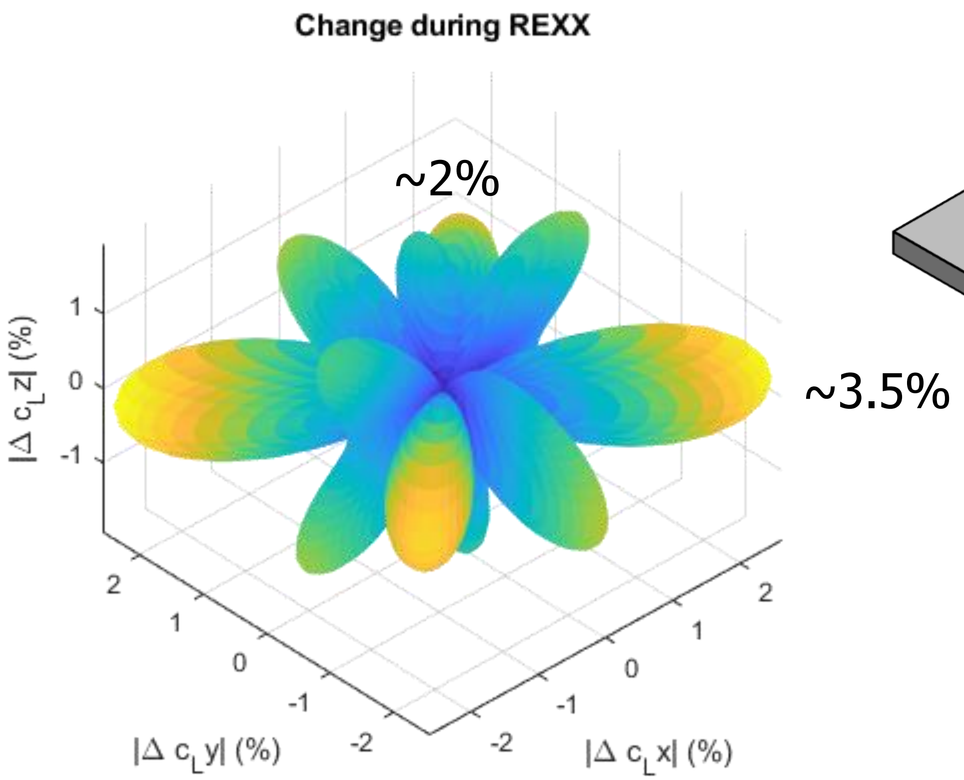
mean results

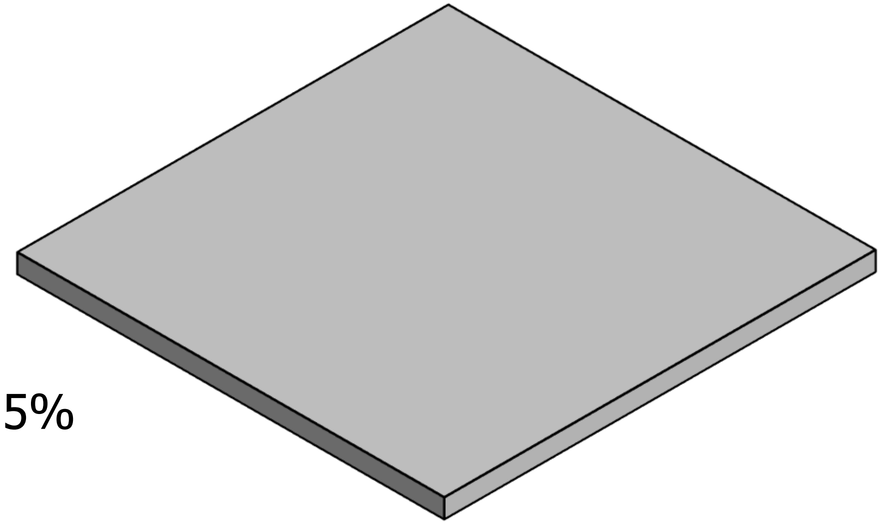




Other directions?

- changes of c_L in normal direction are small
- are other directions more sensitive?
- useful?



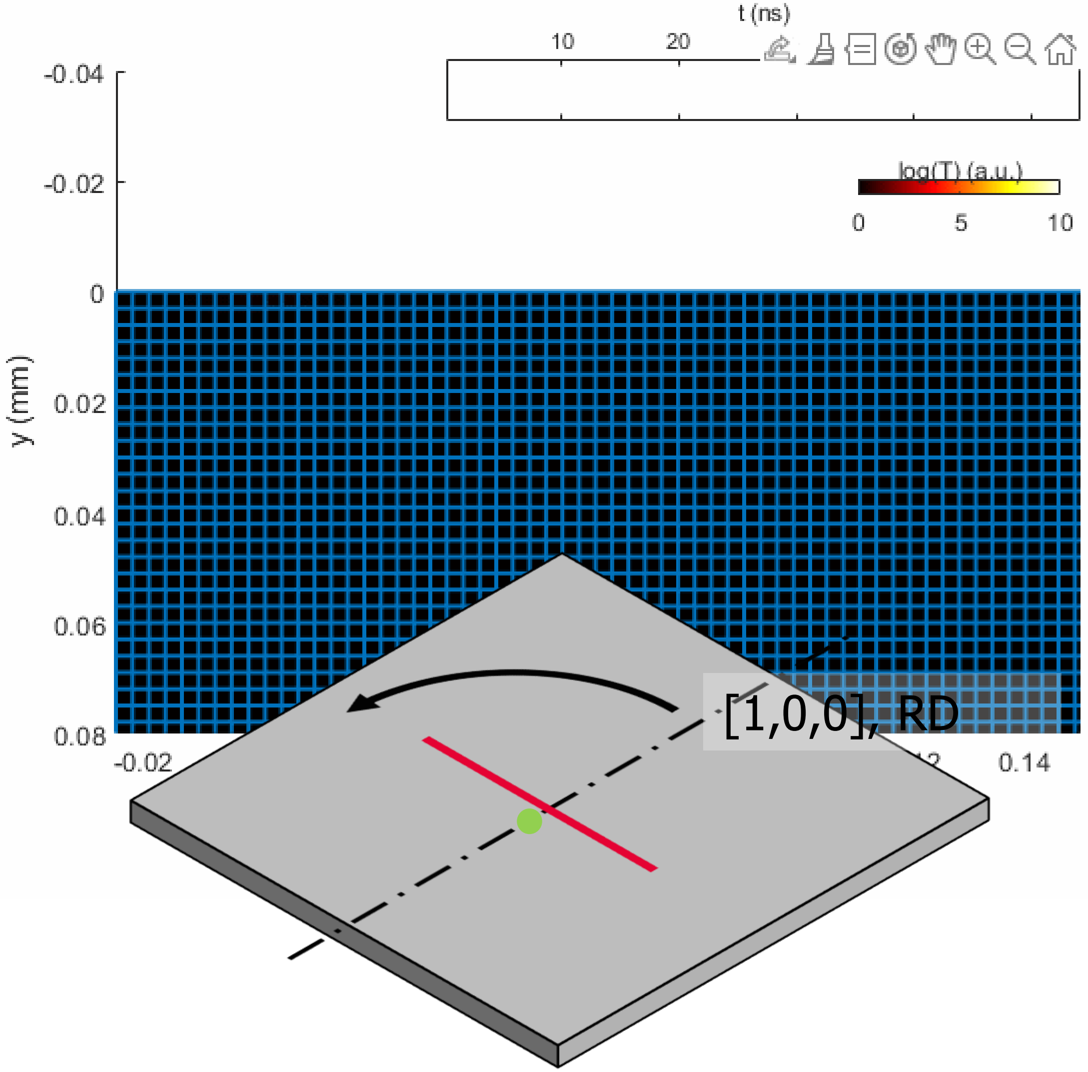


Other modes

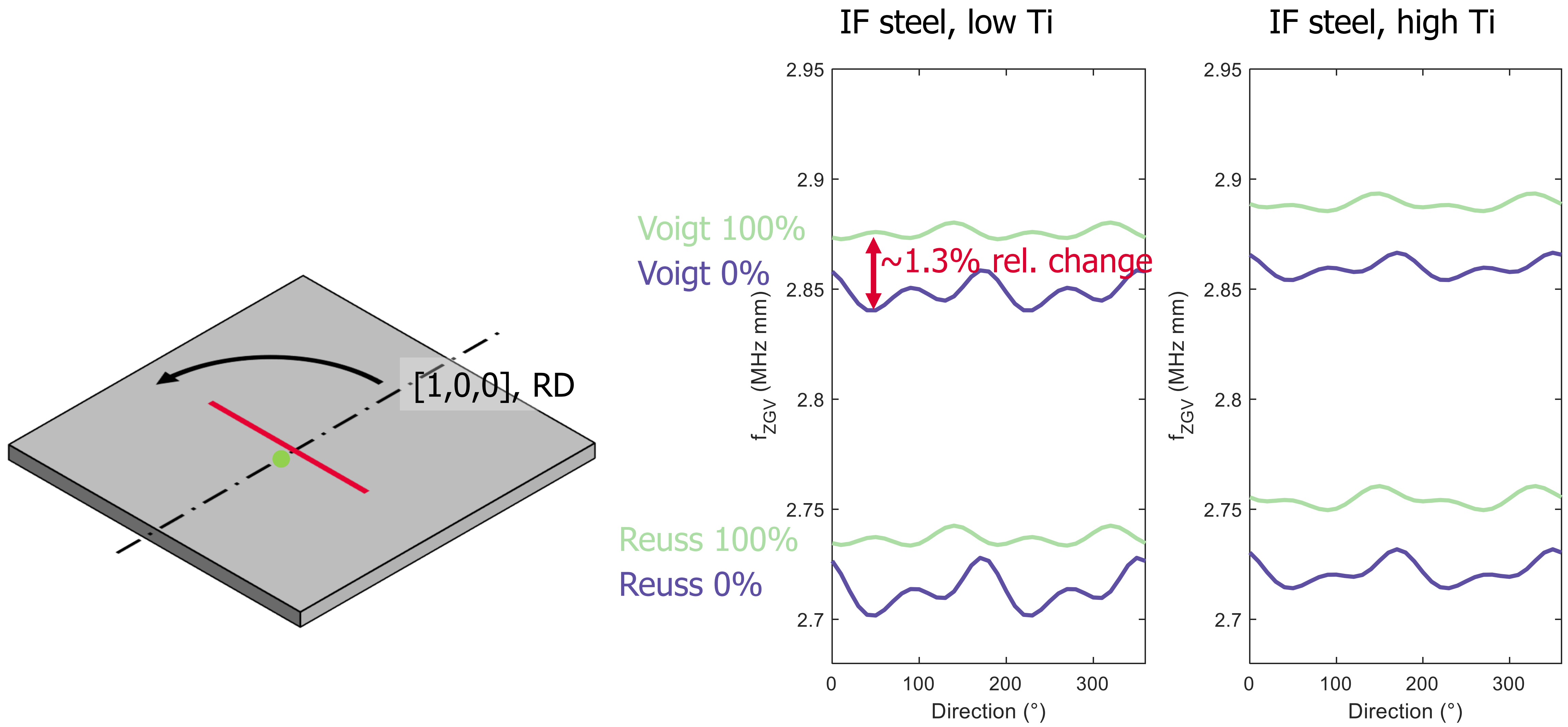
- ZGV resonances
- Surface Acoustic Waves

- Control propagation direction

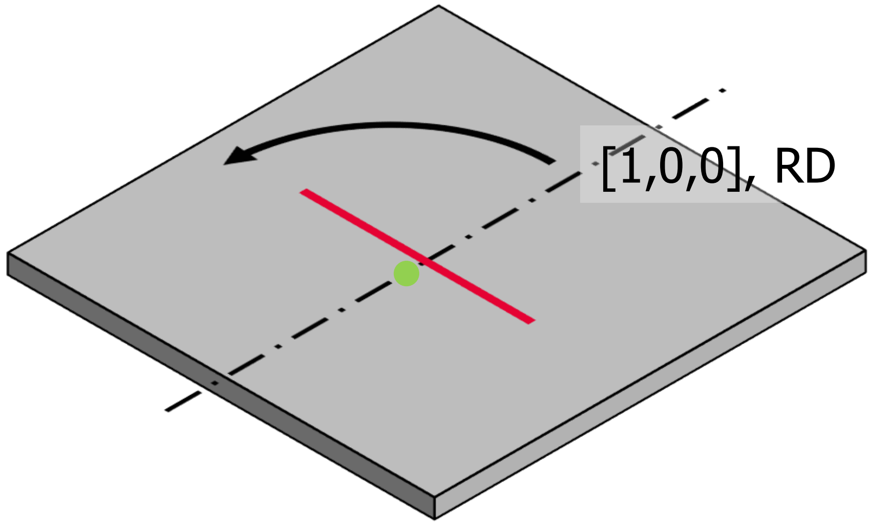
- Same material properties?
- Additional information?
- SNR, ablation?

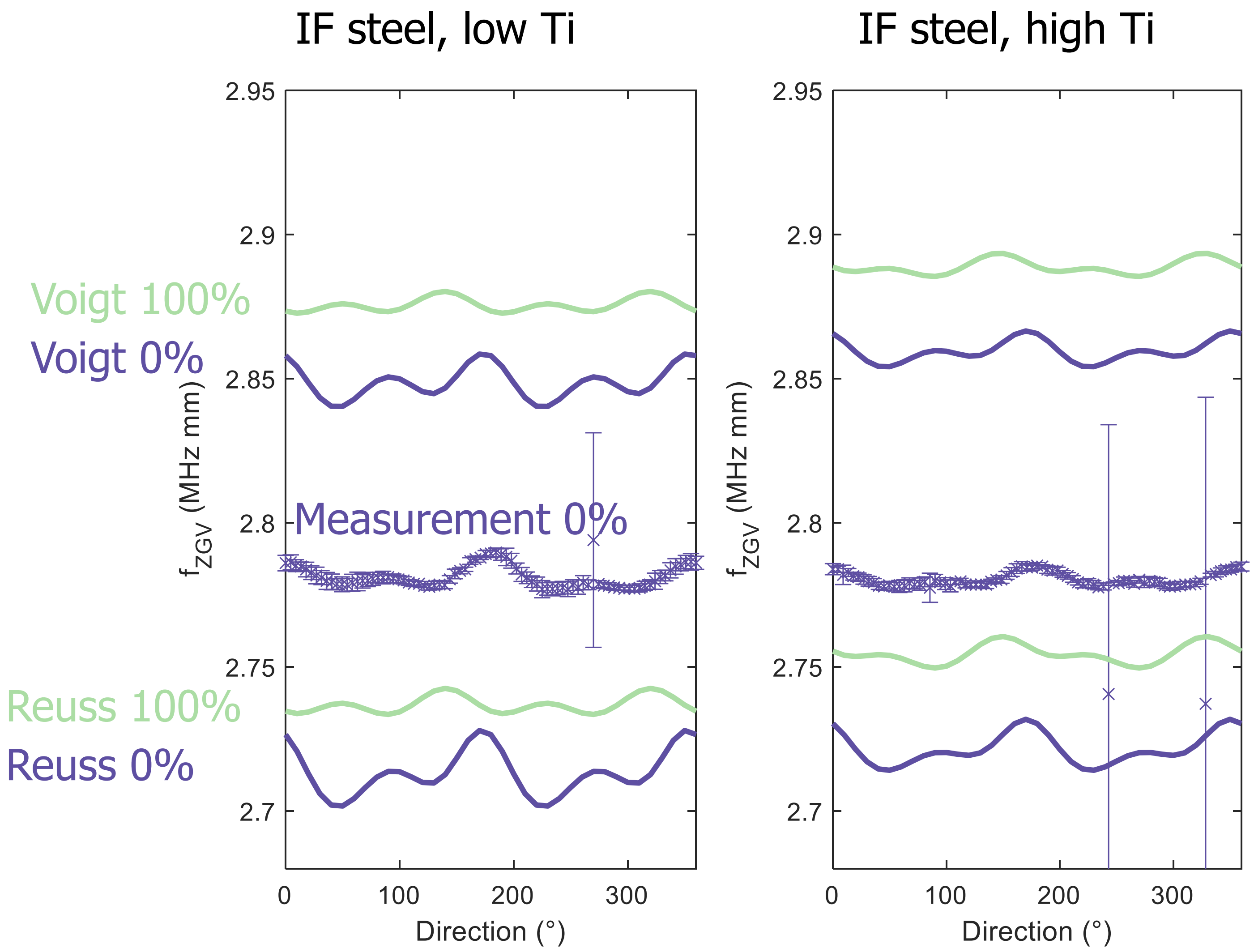


ZGV resonance, ex situ

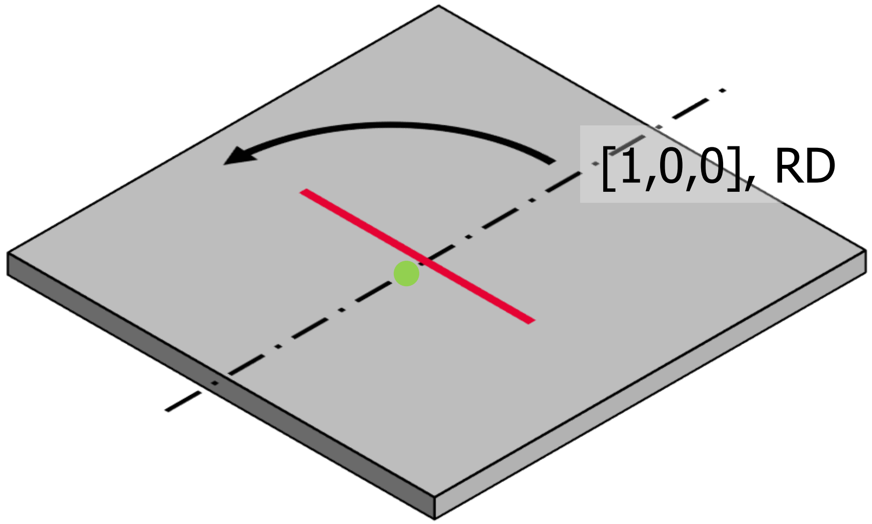


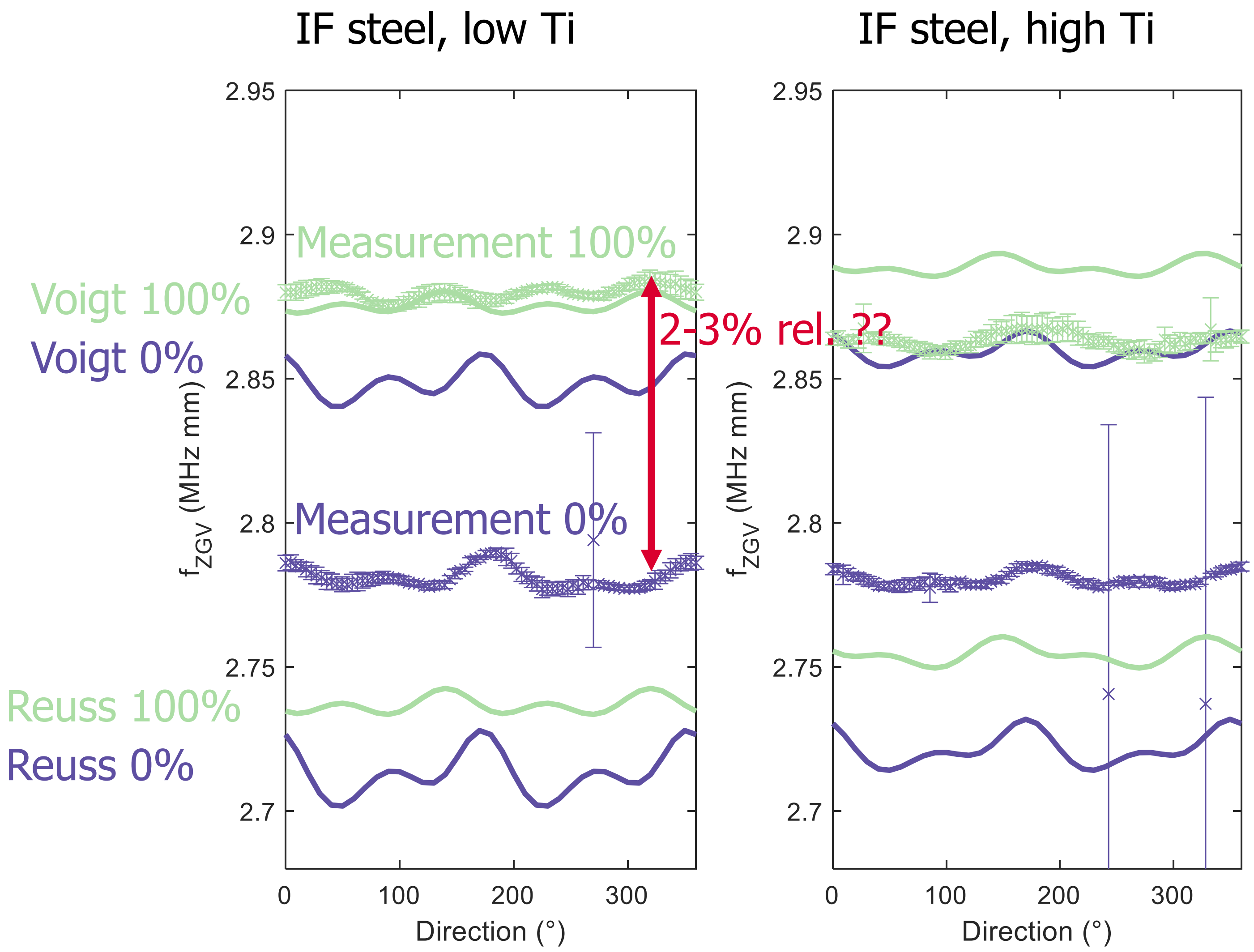
ZGV resonance, ex situ





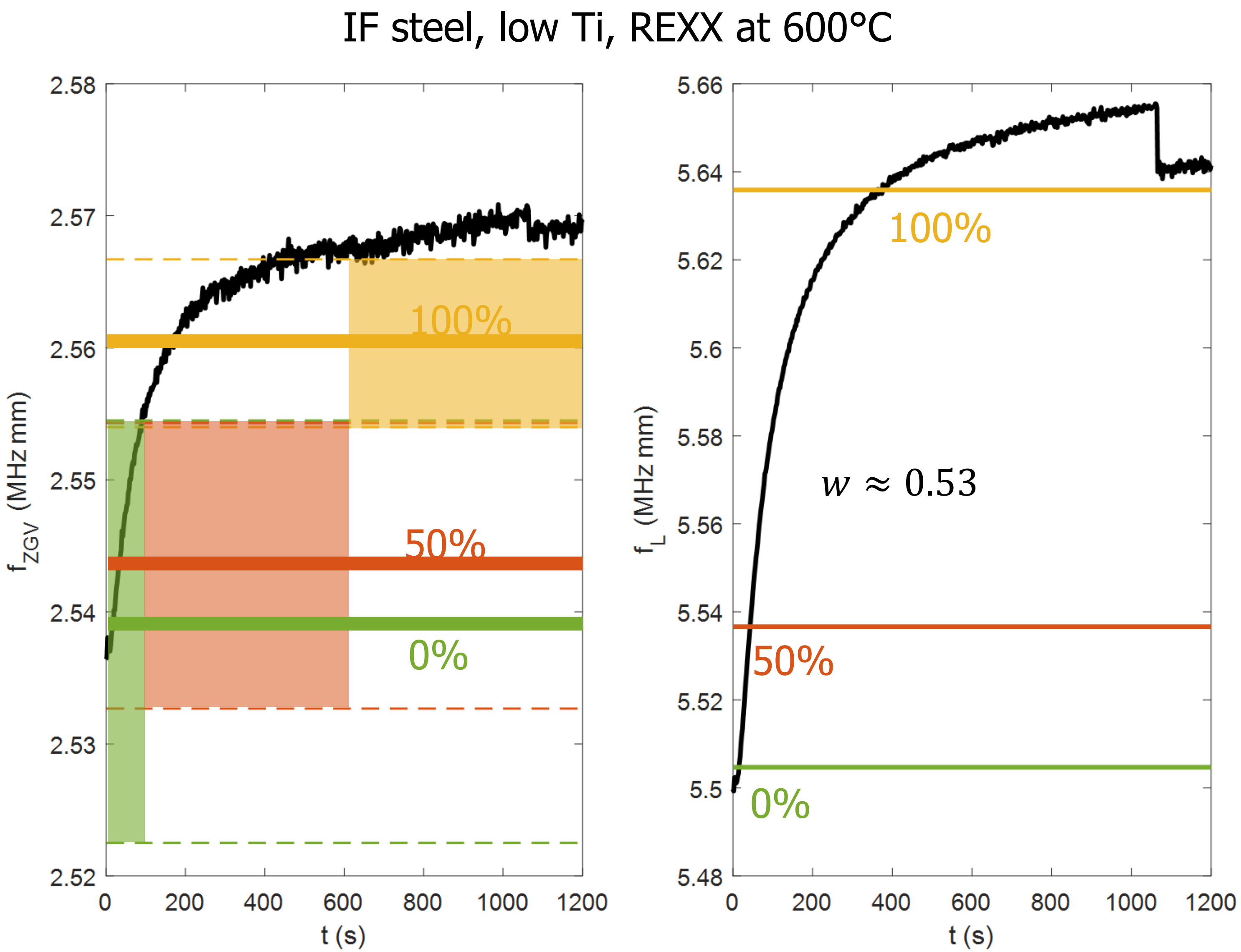
ZGV resonance, ex situ





ZGV resonance, in situ

- Point source



ZGV resonance, in situ

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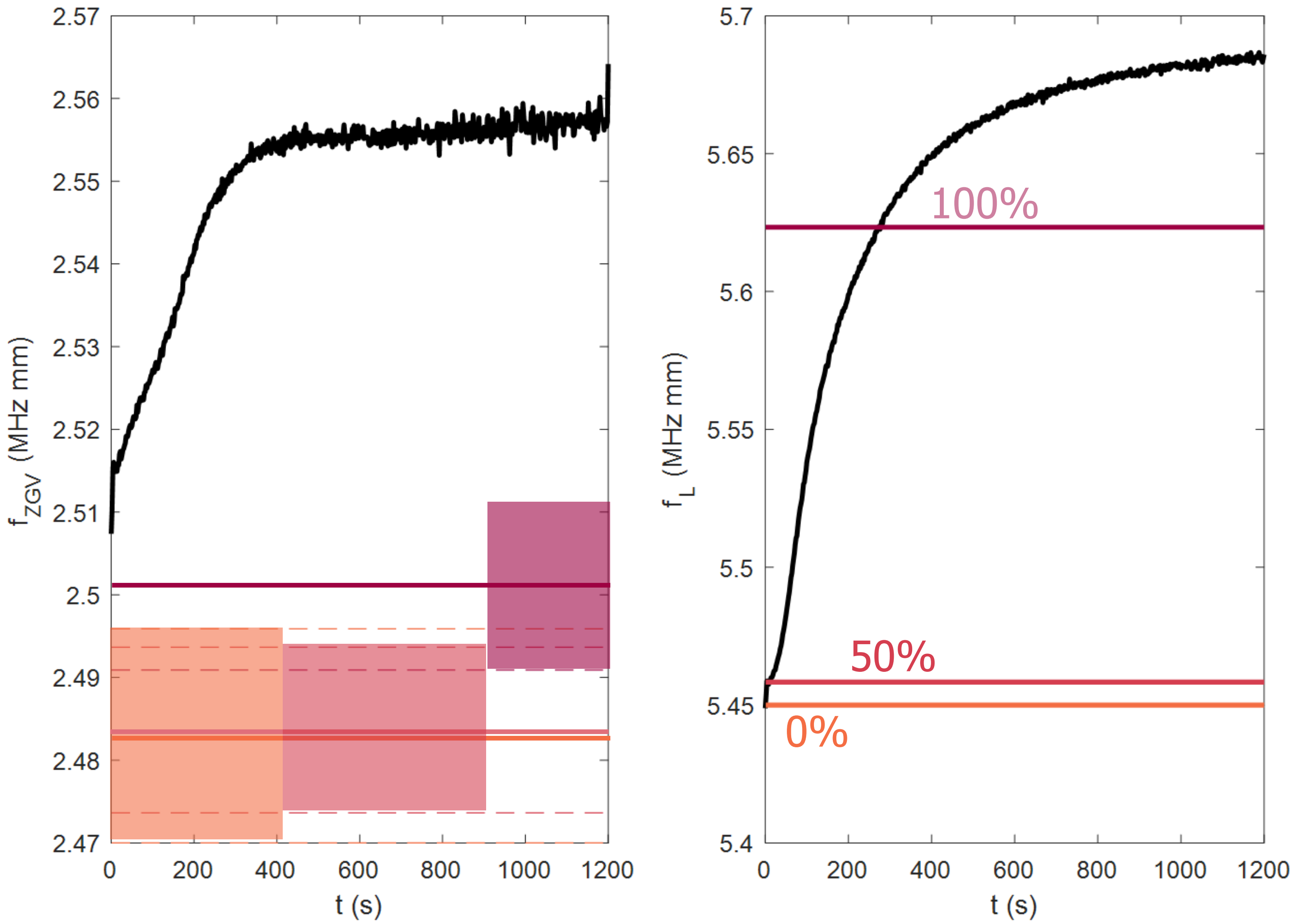
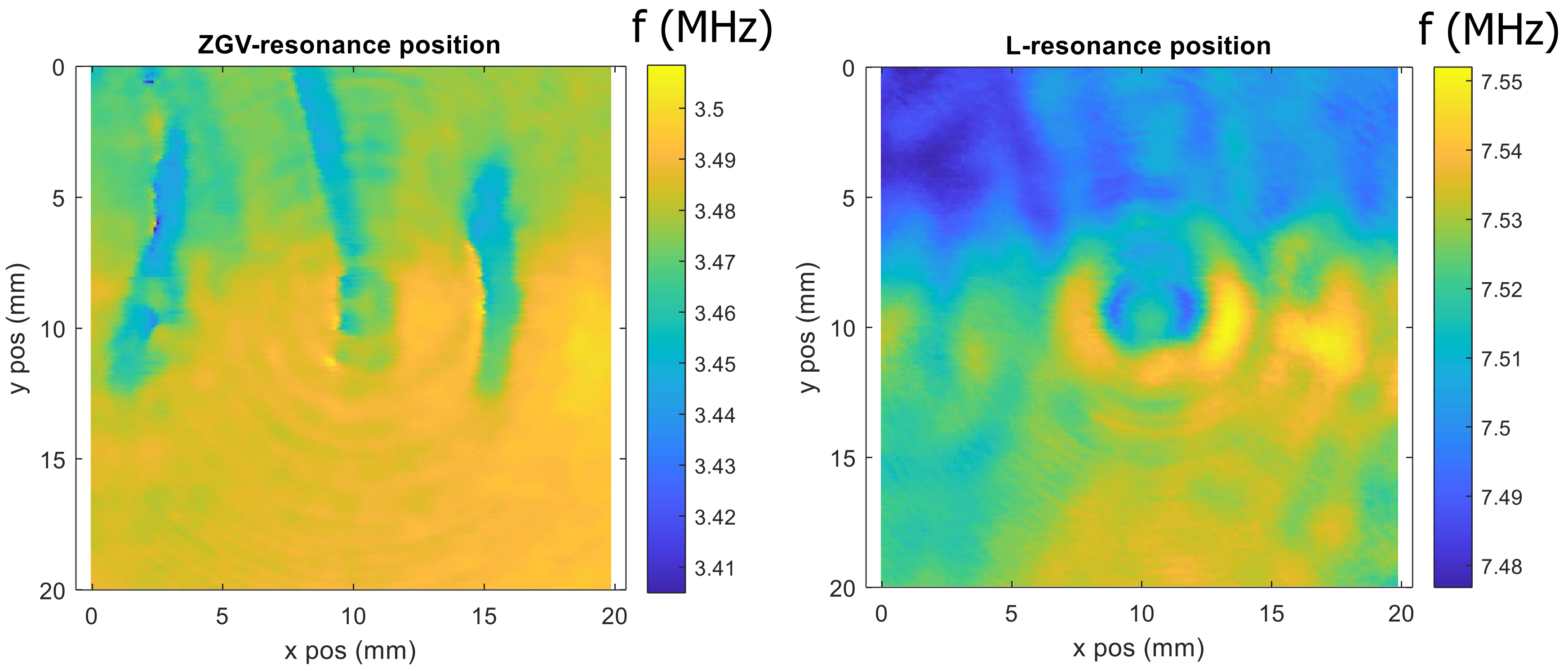
IF steel, high Ti, REXX at 680°C



Homogeneity of samples

- ZGV resonances show local inhomogeneities

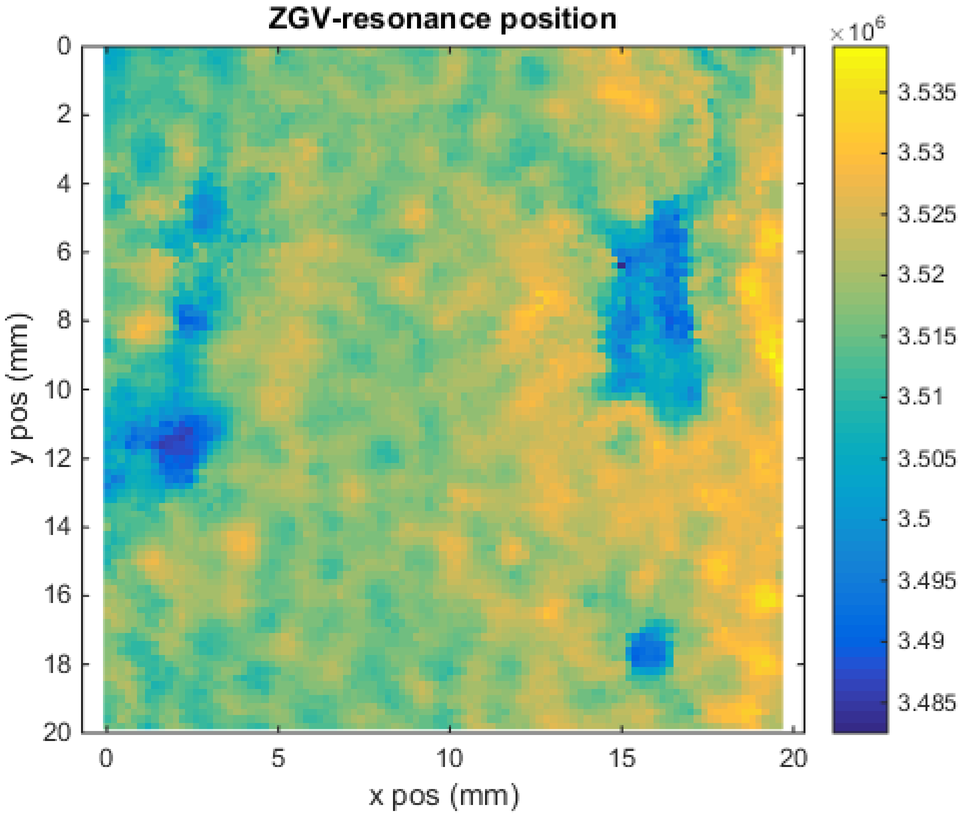
Low Ti IF Steel, 100% REXX



Homogeneity of samples

- Also visible in untreated (cold rolled) samples

Medium Ti IF Steel, 0% REXX



Contributions

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- Measured longitudinal sound velocity in situ on 0.8mm steel sheets, using plate resonances
- Calculated stiffness tensors from EBSD data (0%, 50%, 100% REXX)
- Good agreement of theory and experiment. Small shift of Reuss → Voigt observable?
- Extended to ZGV modes:
  - Ex situ: Good angular agreement, questions remain for 100% REXX
  - In situ: Depending on sample

Our work is funded by the FFG Bridge program:

FO999901377 **STAHLUS**

FFG
Forschung wirkt.

Calculated vs. measured f_{ZGV}- ex situ

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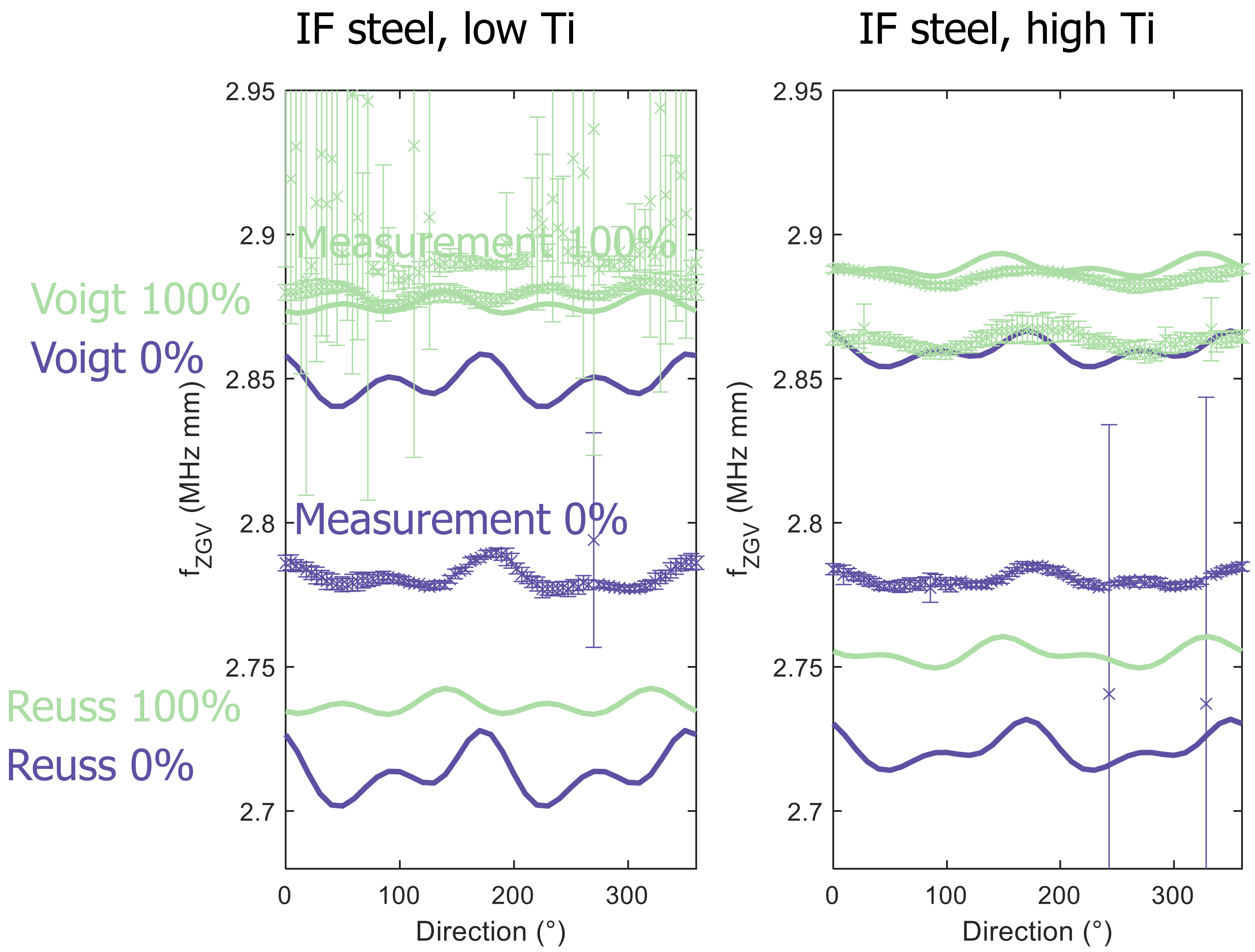
- Directional source (line)
- Rotate sample
- Line scan for each angle

- ?



Calculated vs. measured f_{ZGV}- ex situ

- Directional source (line array)
- Rotate sample