Th.4C_3

# Use of automated feature selection algorithms to calibrate a coating thickness measurement signal in eddy current testing for the inspection of Accident Tolerant Fuel

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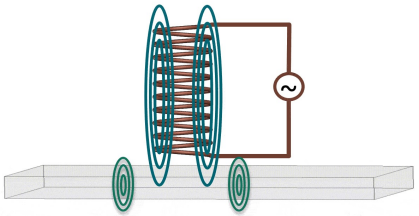
**22.05.2025**

Fraunhofer IKTS

Fraunhofer Institute for Ceramic Technologies and Systems IKTS

Group: Eddy-Current Methods



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# Content

1. Motivation
2. Chrome thickness inspection with ECT
3. Conventional approach
4. Machine Learning approach
5. Conclusion





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## Chapter 01

# Motivation




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# Nuclear accident in Fukushima

Nuclear accident in Fukushima on 11th of March 2011| © opensourceinvestigations.com

Emergency cooling fails

↓

high-temperature steam environment

↓

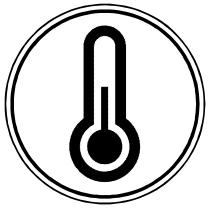
oxidation reaction between cladding tubes and water vapor

↓

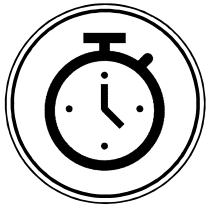
$H^2$ explosion

# Increasing nuclear reactor safety

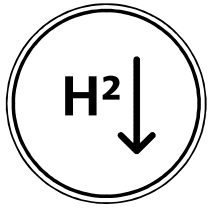
## ATF - Accident tolerant fuel



**Increased temperature resistance**



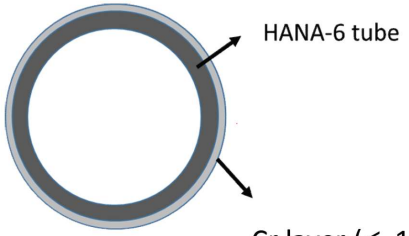
**Improved fuel coping time**




**Suppressed H² uptake**

**Chromium coated zirconium cladding**

- 10 times better **oxidation resistance**




Cr-coated cladding tube| © KEPCO Nuclear Fuel

ATF, Accident Tolerant Fuel| © KEPCO Nuclear Fuel

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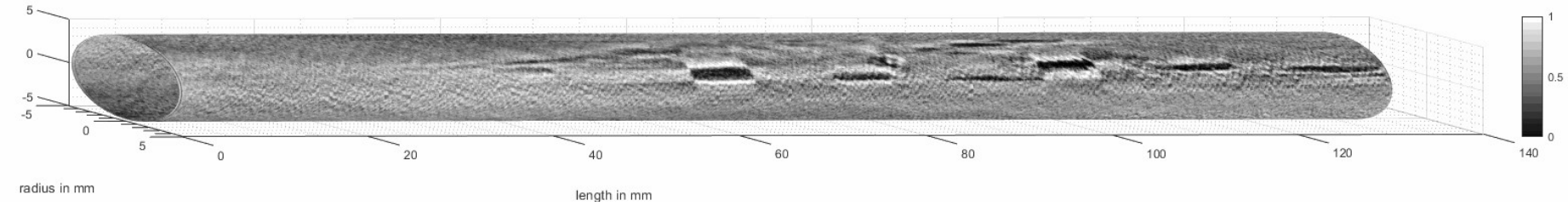
# Quality assurance of chrome coating

- **Chrome thickness measurement** of chrome layers ≤18µm
- Detection of **cracks** and **delaminations** in the chrome coating


Inline inspection system




Eddy-current scan of cracks in chrome layer

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Chapter 02

# Chrome thickness inspection with ECT




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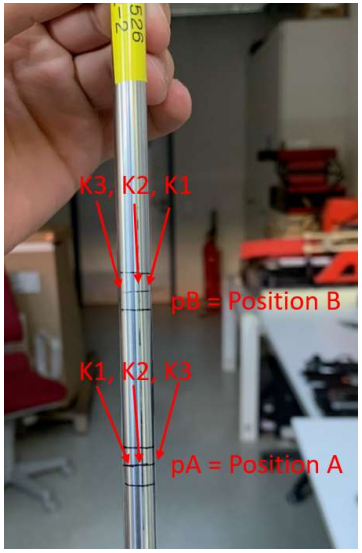
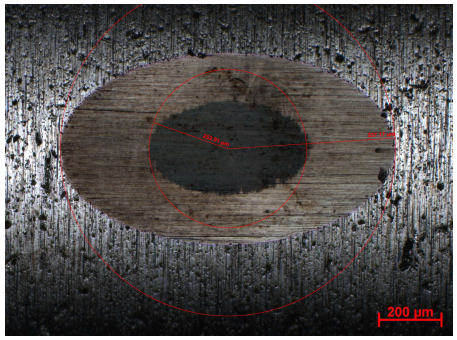
# Reference values

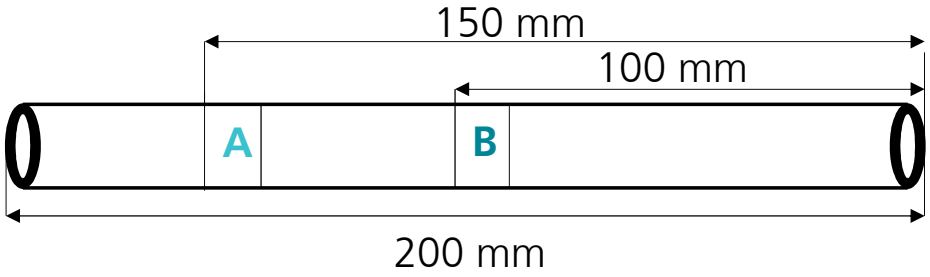



Calo test measurement

## Position A
(Used for Validation)

| Thickness in µm |
|---|
| 3.4 ± 0.3 |
| 4.4 ± 0.5 |
| 4.3 ± 0.7 |
| 10.9 ± 0.7 |
| 11.2 ± 0.7 |
| 11.2 ± 0.7 |
| 11.9 ± 0.8 |
| 12.3 ± 0.7 |
| 11.9 ± 0.7 |
| 14.3 ± 0.8 |
| 14.2 ± 0.8 |
| 15 ± 0.8 |
| 17.1 ± 0.9 |
| 16.7 ± 0.8 |
| 17.2 ± 0.9 |




## Position B
(Used for Training)

| Thickness in µm |
|---|
| 3.5 ± 0.5 |
| 4.2 ± 0.4 |
| 4.5 ± 0.4 |
| 11 ± 0.7 |
| 11.3 ± 0.7 |
| 10.9 ± 0.6 |
| 11.7 ± 0.7 |
| 12.3 ± 0.7 |
| 12 ± 0.7 |
| 14.3 ± 0.8 |
| 14.1 ± 0.8 |
| 14.1 ± 0.8 |
| 17.1 ± 0.9 |
| 16.8 ± 0.9 |
| 17.4 ± 0.9 |

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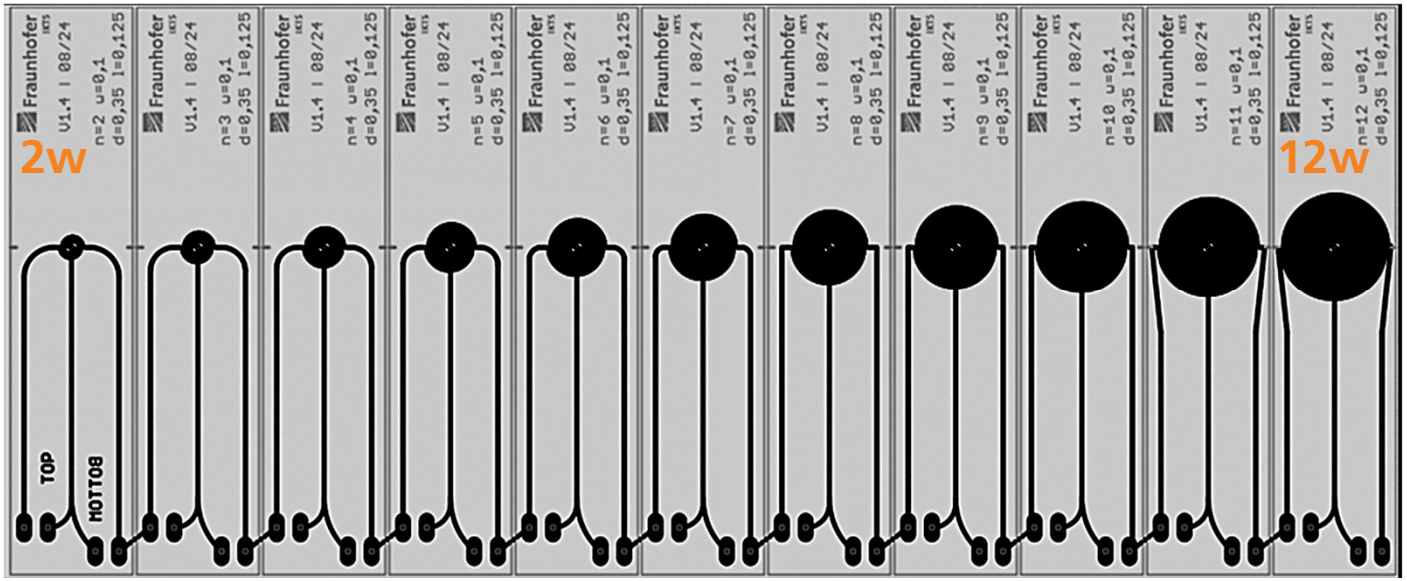
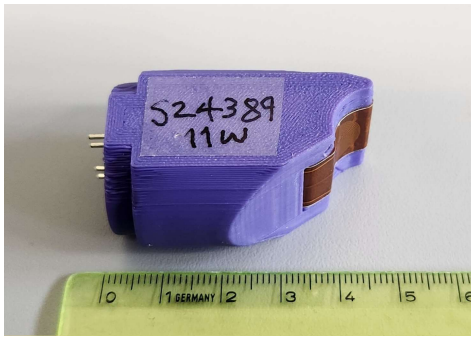
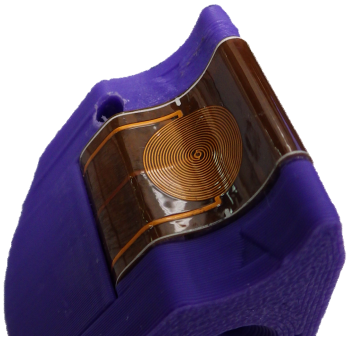
# Eddy-current probes




Layout of circular coils printed as flexible PCBs.



Flexible PCB coil mounted on concave probe housing

- A total of 11 flexible coil sensors with different numbers of windings (from 2w to 12w).
- The housing is 3D printed and adapts to the curvature of the tube to minimize lift-off and tilt effects.

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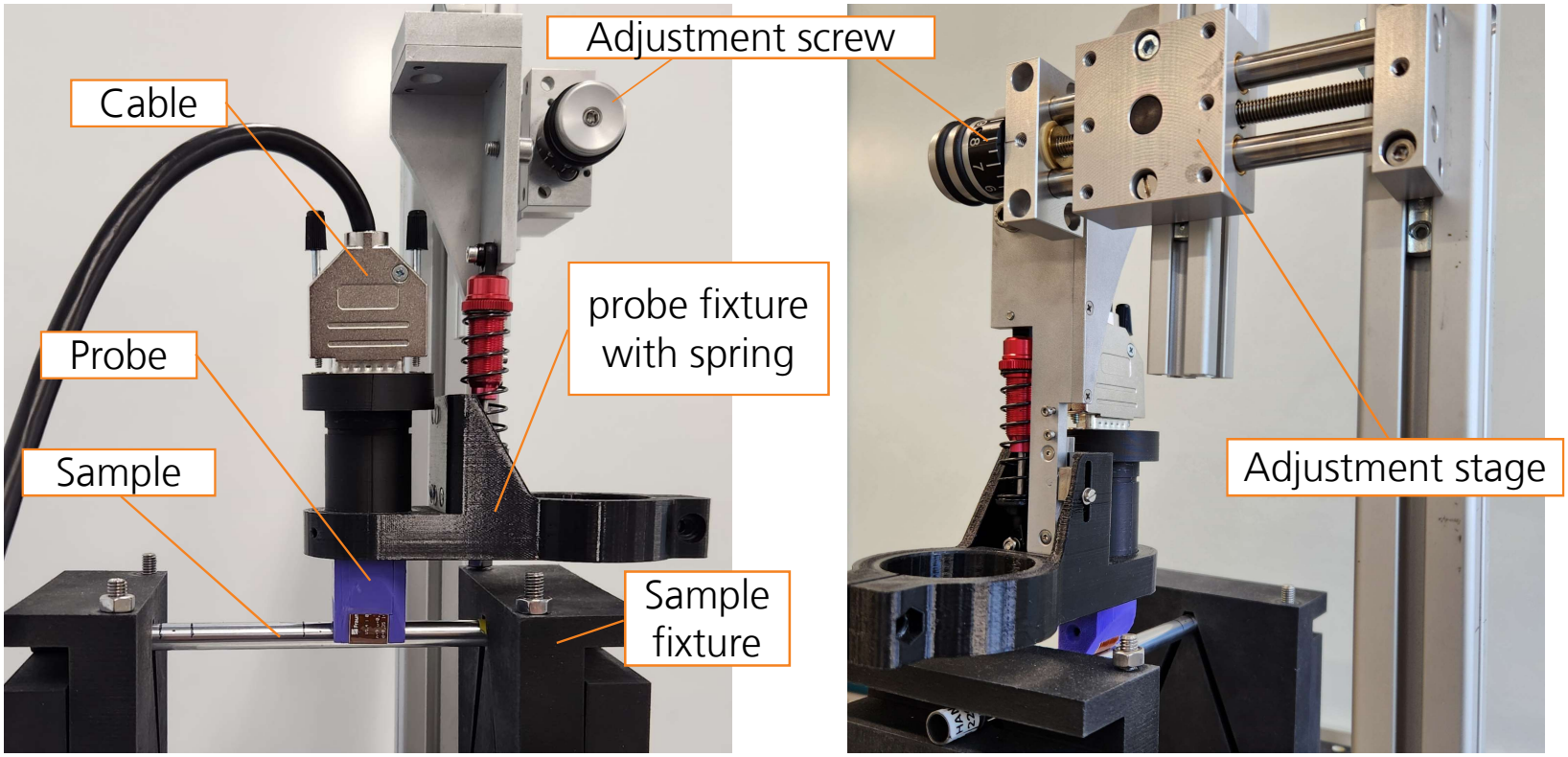
# Experimental setup




Experimental setup

- All samples have been measured 400 times with the 11 flexible coil sensors at the same two positions.



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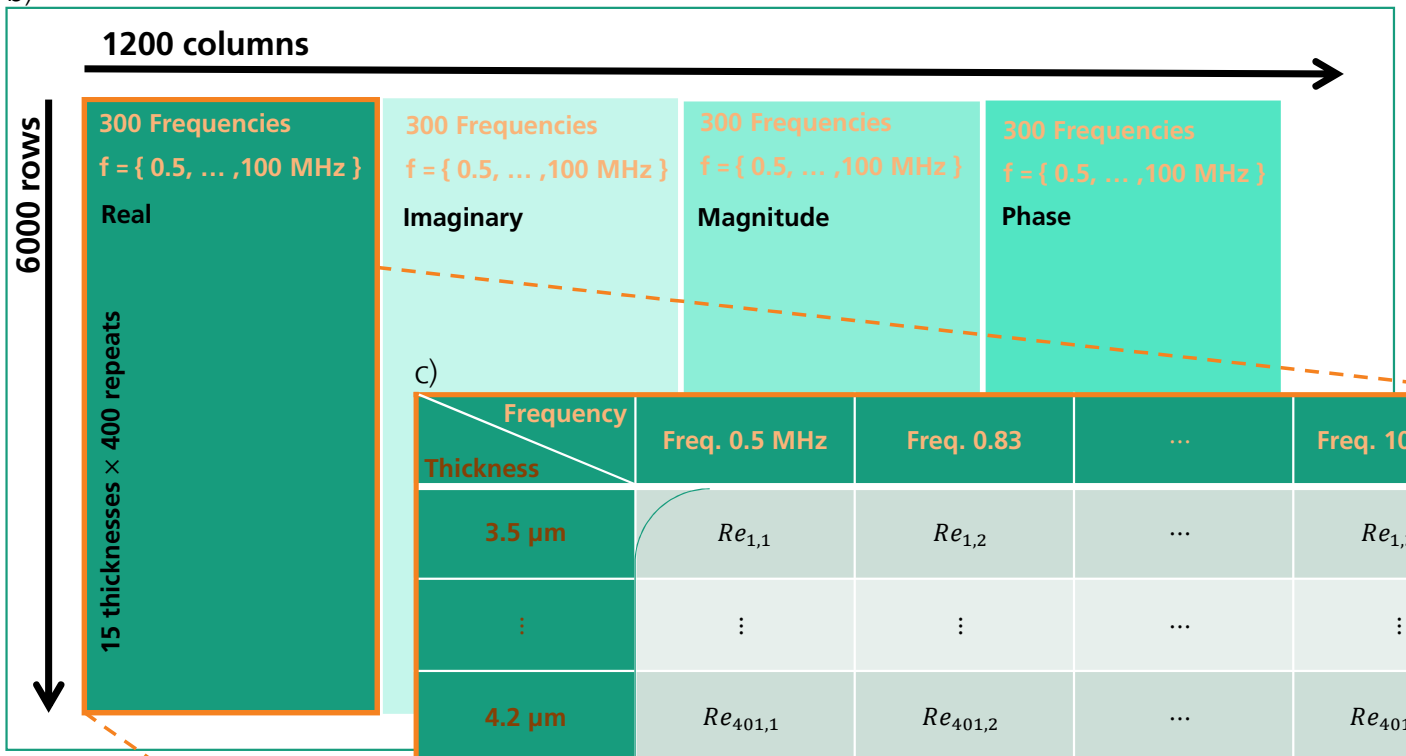
# Data structure

- Complex measurement data ( real + imaginary part of measured voltage)
- Calculated magnitude and phase values

a)

| Thickness in µm |
|---|
| 3,5 |
| 4,2 |
| 4,5 |
| 11 |
| 11,3 |
| 10,9 |
| 11,7 |
| 12,3 |
| 12 |
| 14,3 |
| 14,1 |
| 14,1 |
| 17,1 |
| 16,8 |
| 17,4 |

b)




c)

| Frequency / Thickness | Freq. 0.5 MHz | Freq. 0.83 | … | Freq. 100 MHz |
|---|---|---|---|---|
| 3.5 µm | $Re_{1,1}$ | $Re_{1,2}$ | … | $Re_{1,300}$ |
| ⋮ | ⋮ | ⋮ | … | ⋮ |
| 4.2 µm | $Re_{401,1}$ | $Re_{401,2}$ | … | $Re_{401,300}$ |
| ⋮ | ⋮ | ⋮ | … | ⋮ |
| 17.4 µm | $Re_{6000,1}$ | $Re_{6000,2}$ | … | $Re_{6000,300}$ |

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Chapter 03

# Conventional approach




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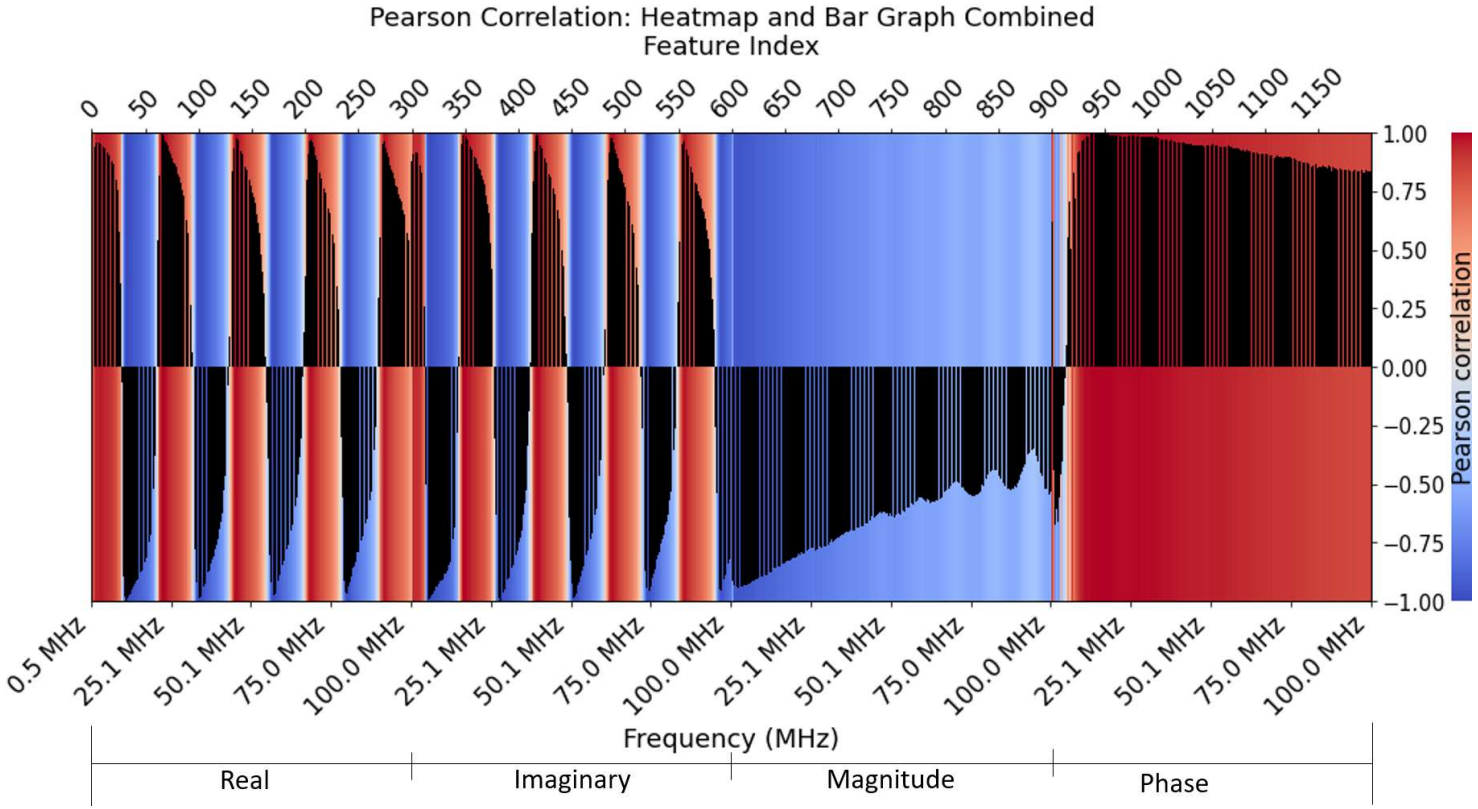
# Data analysis




- Pearson-correlation: Measure of linear correlation (-1 negative linearity to +1 positive linearity)
➔The closer to |1|, the more relevant the feature is

Analysing the linearity of characteristics using Pearson correlation coefficients

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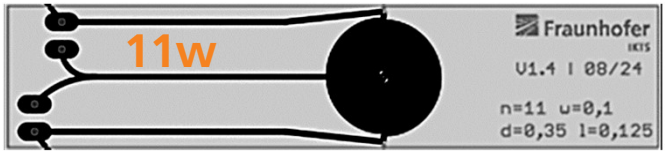
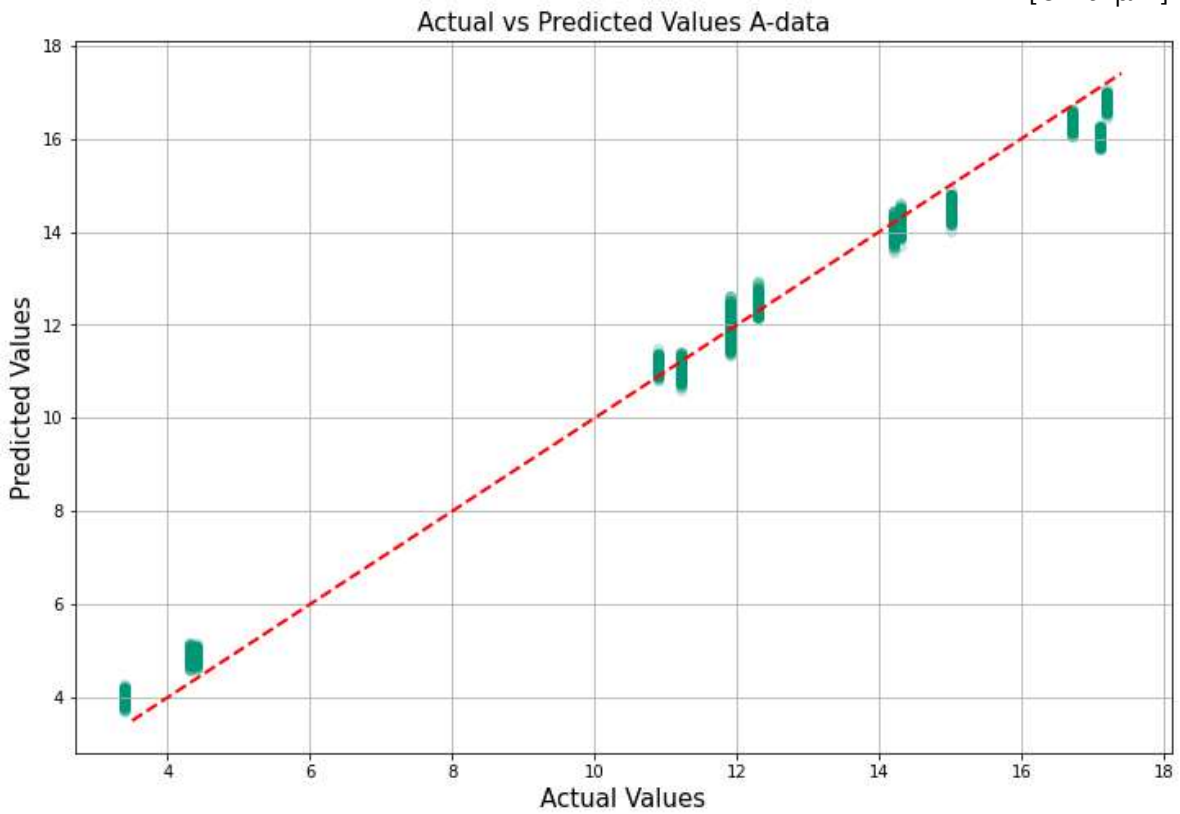
# Conventional calibration technique – $R^2$

- Only **one selected feature** (imaginary part at 28.12 MHz) with maximum correlation and use of simple linear regression




[Unit: µm]




Test R^2 Score: [0.9892352632502371]
selected Features: [['I 28.12 MHz']]

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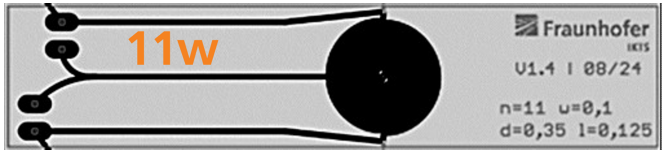
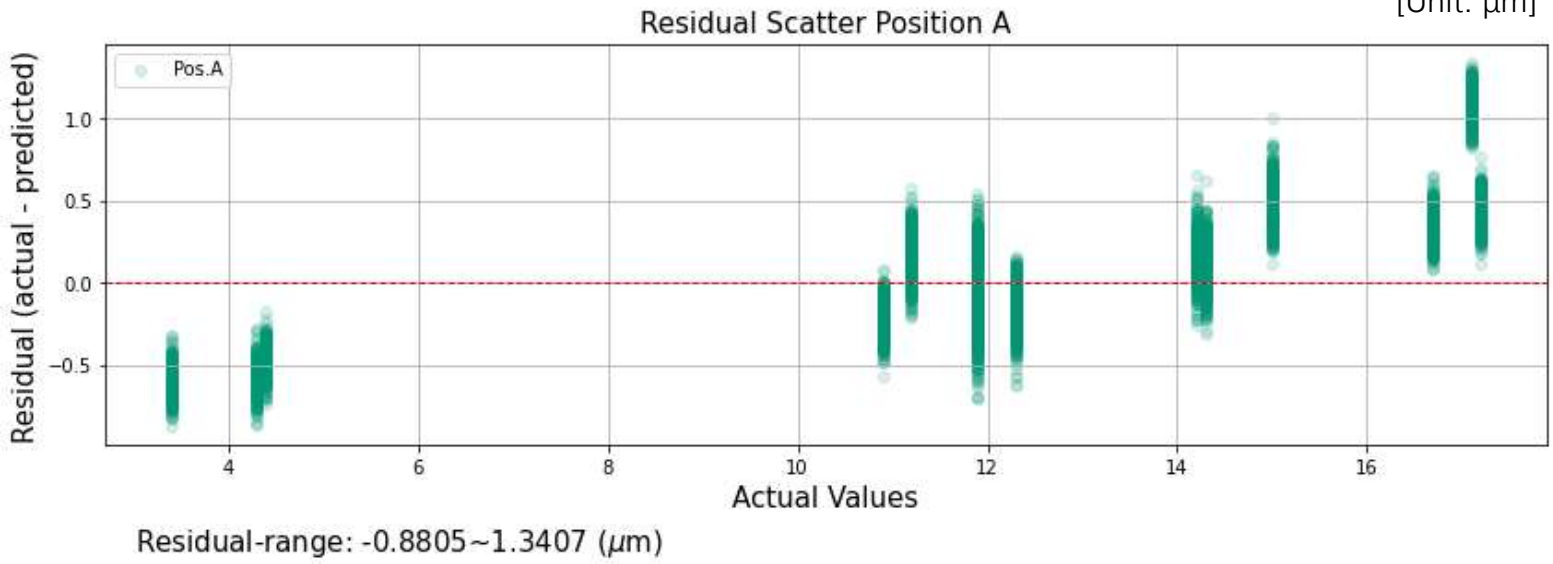
# Conventional calibration technique – Residuals




- Only **one selected feature** (imaginary part at 28.12 MHz) with maximum correlation and use of simple linear regression

[Unit: µm]



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Chapter 04

# Machine Learning approach




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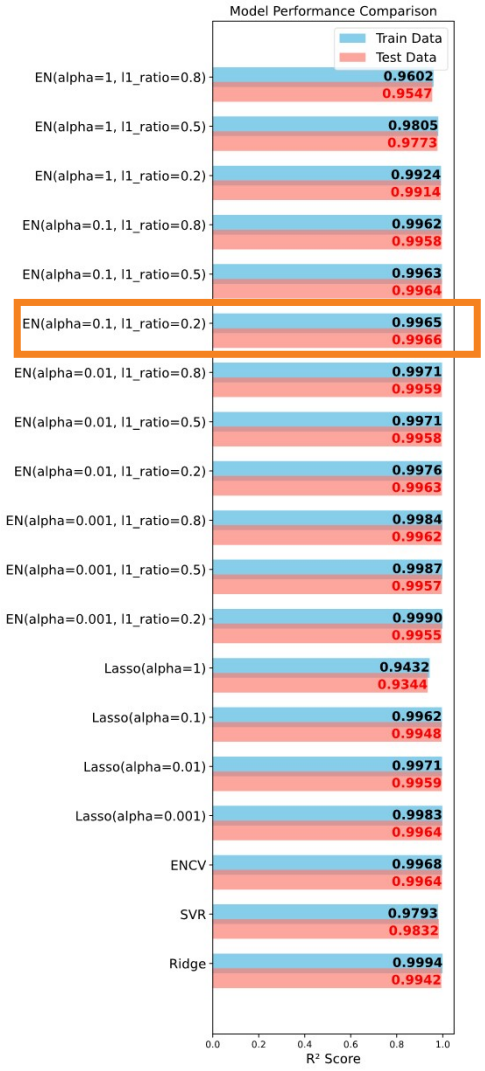
# Selection of linear regression model

Comparison of **4 different linear regression models**:

- ElasticNet (EN)
- Lasso
- Support Vector Regressor (SVR)
- Ridge

- For the models ElasticNet and Lasso the hyperparameters for regularization strength have been varied.

**Selected model**: ElasticNet with alpha=0.1 and l1-ratio=0.2 (best on Test Data)







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# Preselection of features

```
Kbest Selected Frequency Higher score order:
 ['I 28.12 MHz', 'R 11.15 MHz', 'P 14.48 MHz', 'I 16.81 MHz', 'P 13.15 MHz', 'P 13.48 MHz', 'P 12.81 MHz',
'P 14.14 MHz', 'R 22.46 MHz', 'P 15.47 MHz']
Feature combination (32,) R² score: 0.9936488048095965
Feature combination (66,) R² score: 0.9920090257544869
Feature combination (349,) R² score: 0.9931295431498836
```

1. Preselecting 10 features with maximum linear correlation

⋮

**In total 1023 combinations with increasing feature count**

```
Feature combination (32, 66, 349, 383, 937, 938, 939, 942, 945) R² score: 0.9965396884145908
Feature combination (32, 66, 349, 383, 937, 938, 941, 942, 945) R² score: 0.9965137909530949
Feature combination (32, 66, 349, 383, 937, 939, 941, 942, 945) R² score: 0.9964519048116682
Feature combination (32, 66, 349, 383, 938, 939, 941, 942, 945) R² score: 0.9965316576262976
Feature combination (32, 66, 349, 937, 938, 939, 941, 942, 945) R² score: 0.9964415806478921
Feature combination (32, 66, 383, 937, 938, 939, 941, 942, 945) R² score: 0.9965376901367647
Feature combination (32, 349, 383, 937, 938, 939, 941, 942, 945) R² score: 0.9965377186349851
Feature combination (66, 349, 383, 937, 938, 939, 941, 942, 945) R² score: 0.996395869871614
Feature combination (32, 66, 349, 383, 937, 938, 939, 941, 942, 945) R² score: 0.9965376412423308
```

2. Evaluation of all combinations using $R^2$




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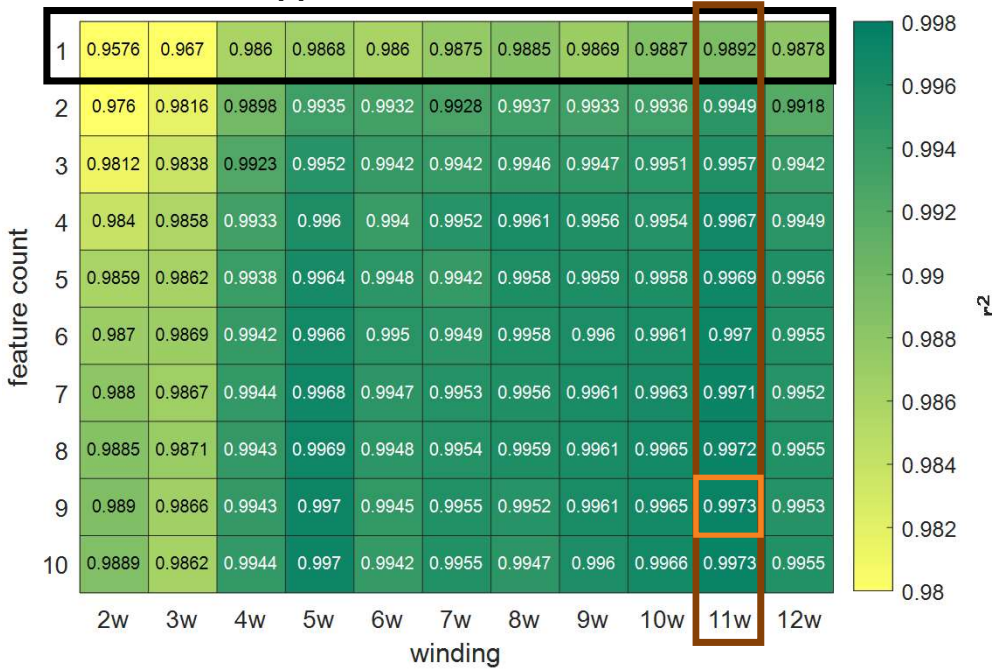
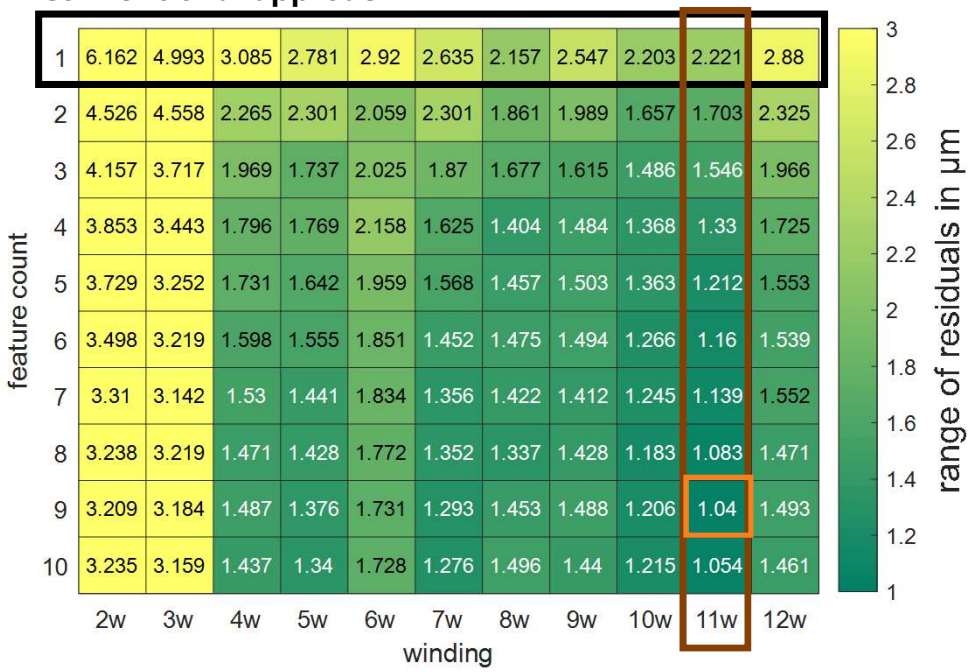
# Probe and feature space evaluation

**Conventional approach**




**Conventional approach**




- Probe with **11 coil turns** has best r² score and smallest range of residuals.
- For this probe the **combination of 9 features** provides the best results.

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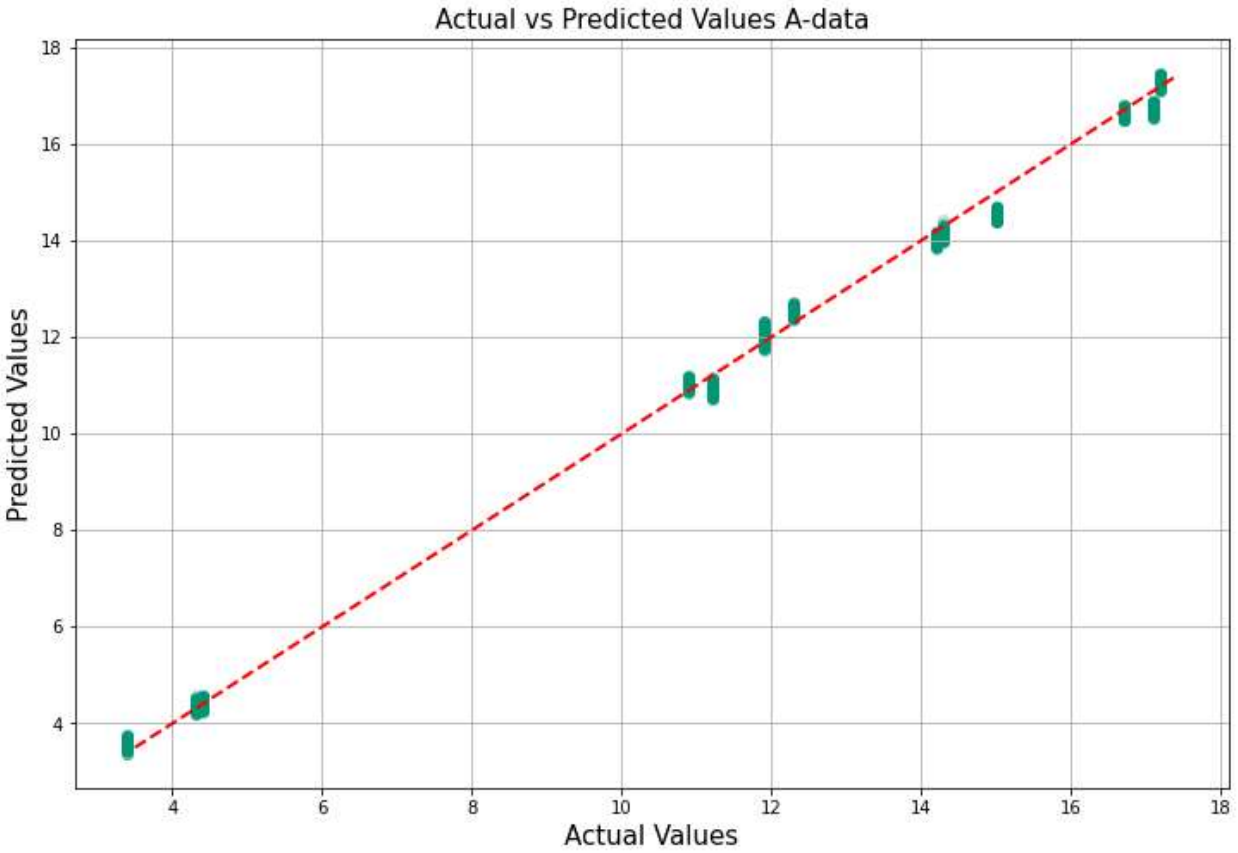
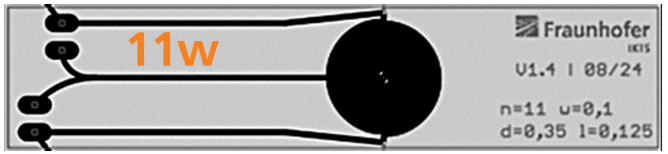
# Result: $R^2$

[Unit: µm]




- **9 selected features** with maximum correlation and use of multiple linear regression




Test R^2 Score: [0.9972638001573008]
selected Features: [['R 11.15 MHz', 'I 16.81 MHz', 'I 28.12 MHz', 'P 12.81 MHz', 'P 13.15 MHz', 'P 13.48 MHz', 'P 14.14 MHz', 'P 14.48 MHz', 'P 15.47 MHz']]

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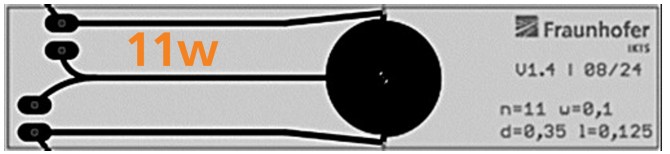
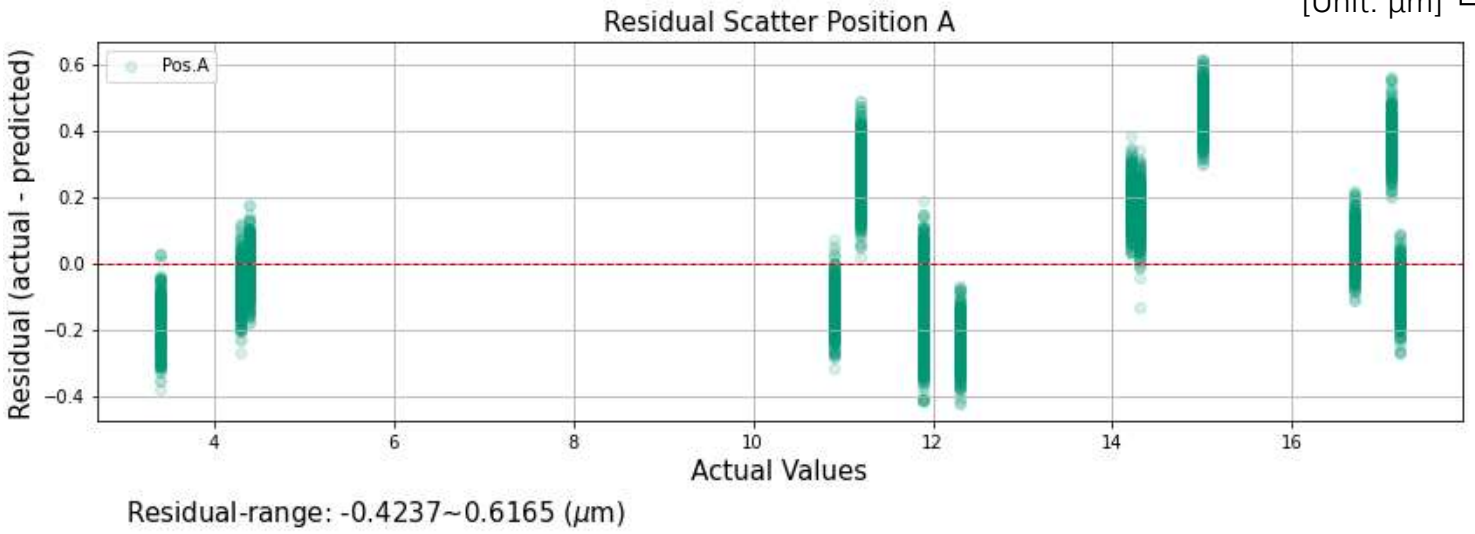
# Result: Residuals




- **9 selected features** with maximum correlation and use of multiple linear regression

[Unit: µm]




Residual-range: -0.4237~0.6165 (µm)

- For the probe with **11 coil turns** the range of residuals has been reduced by **more than 50%** by the use of **9 features** compared to only one selected feature.

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## Chapter 05

# Conclusion




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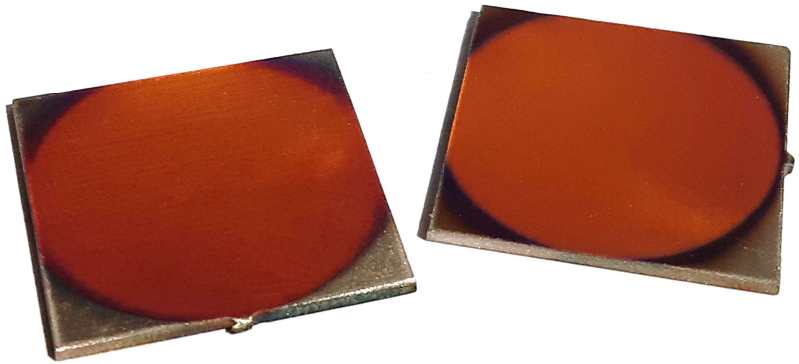
# Conclusion

## Achievements

✓ Selected best probe configuration – 11 coil turns
✓ Selected best feature space – 9 features
✓ Performance improvement of a factor of two compared to conventional approach

## Further applications

- Monitoring layer thicknesses in pulsed laser deposition processes
- Battery foil inspection
- Or any other kind of thin coating layers



Cu thin films deposited with PLD

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https://s.fhg.de/eddycus

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