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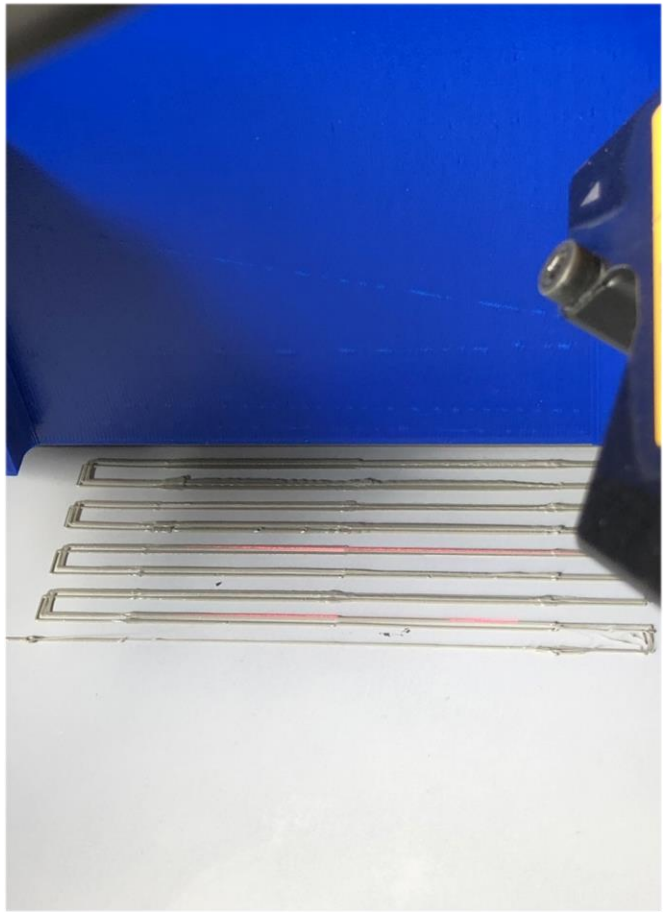

Influence of single-filament dimensions on geometrical density as a quality criterion for fused filament fabrication

Robert H. Schmitt[1], **Kilian Geiger**[1], Dominik Wolfschläger[1], Martin Peterek[1]

Joint Special Interest Group meeting between euspen and ASPE
Advancing Precision in Additive Manufacturing Ecole Centrale de Nantes, France
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K.Geiger@wzl.rwth-aachen.de

[1]*Laboratory for Machine Tools and Production Engineering of RWTH Aachen University, Germany*

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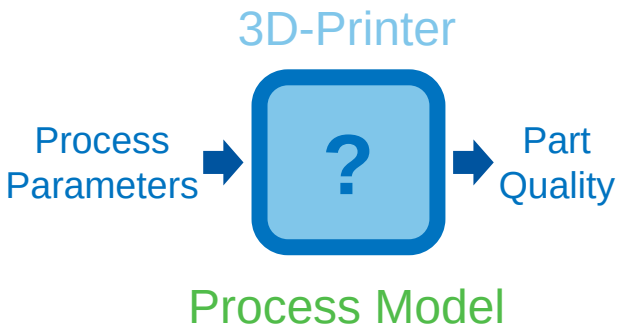
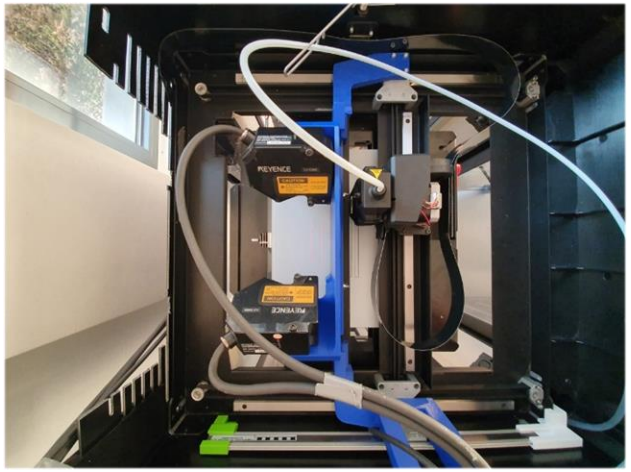
Problem





- Goal
  - Lower the entry barrier into polymer additive manufacturing for small and medium-sized enterprises
- Our approach
  - Understand influence of print process parameters on single filaments
  - Analyze interaction between neighboring and stacked filaments
  - Create **model** to predict part quality (i.e. porosity and dimensional accuracy) based on print process parameters
- Implementation
  - Integration of two laser line triangulation scanners (LLS) into a fused filament fabrication printer
  - Scanning of printed filaments
  - First, offline analysis of recorded to generate process knowledge
  - Laser, online close loop error detection

Related work

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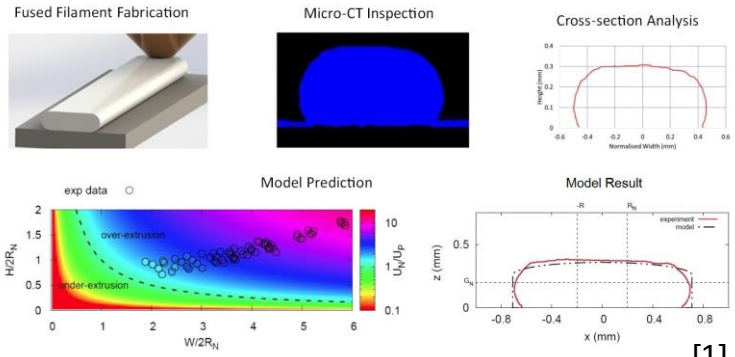
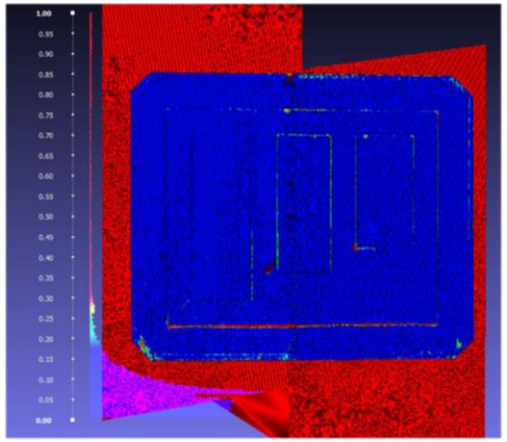


[1]



- Related work
  - Computational simulations and mathematical models exist but only few were validated against experimental data [1]
  - Hebda et. al achieved R^2 values of 94.1% and 84.7% for a model describing the width and height of filaments [2]
    - Most of the experiments were conducted with very high filament feed rates and therefore under over extruding conditions
    - The printed filaments were captures with a computer tomography system, which can only be used for finished prints

- Previous work at WZL
  - Comparison of scanned filaments with simulated structure based on g-code
  - But:
    - Invalidated model for filament shape
    - No information on the cause-effect relation
    - Massive amount of data not applicable for analysis during print process

[1] B. N. Turner, R. Strong, and S. A. Gold, “A review of melt extrusion additive manufacturing processes: I. Process design and modeling,” *Rapid prototyping journal*, vol. 20, no. 3, pp. 192–204, 2014.
[2] M. Hebda, McIlroy Claire, B. Whiteside, F. Caton-Rose, and P. Coates, “A method for predicting geometric characteristics of polymer deposition during fused-filament-fabrication,” *Additive Manufacturing*, no. 27, pp. 99–108, May. 2019.

Experimental Setup

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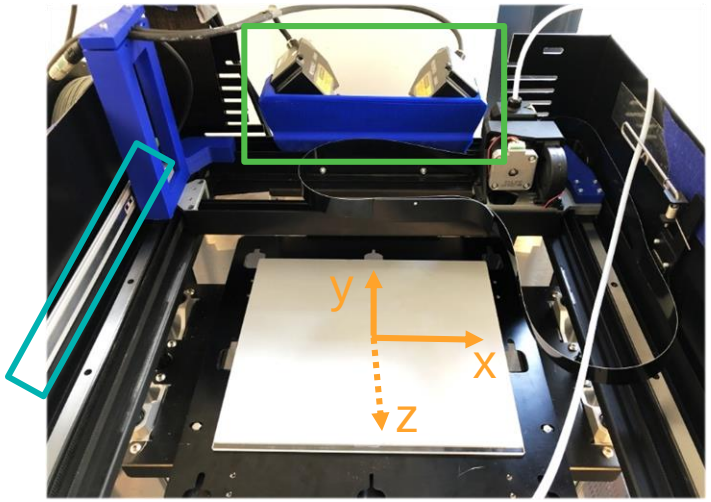
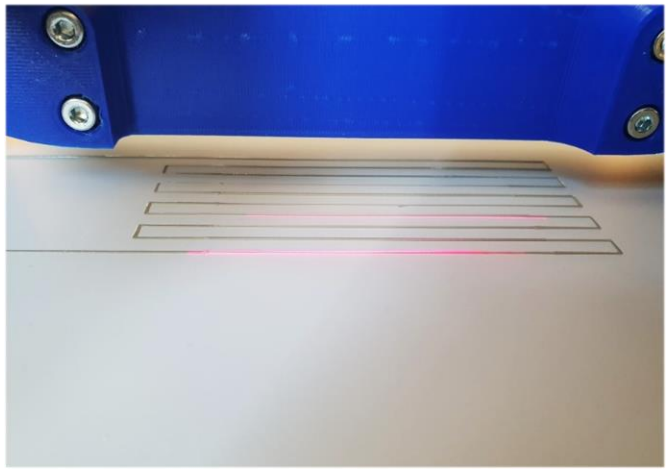
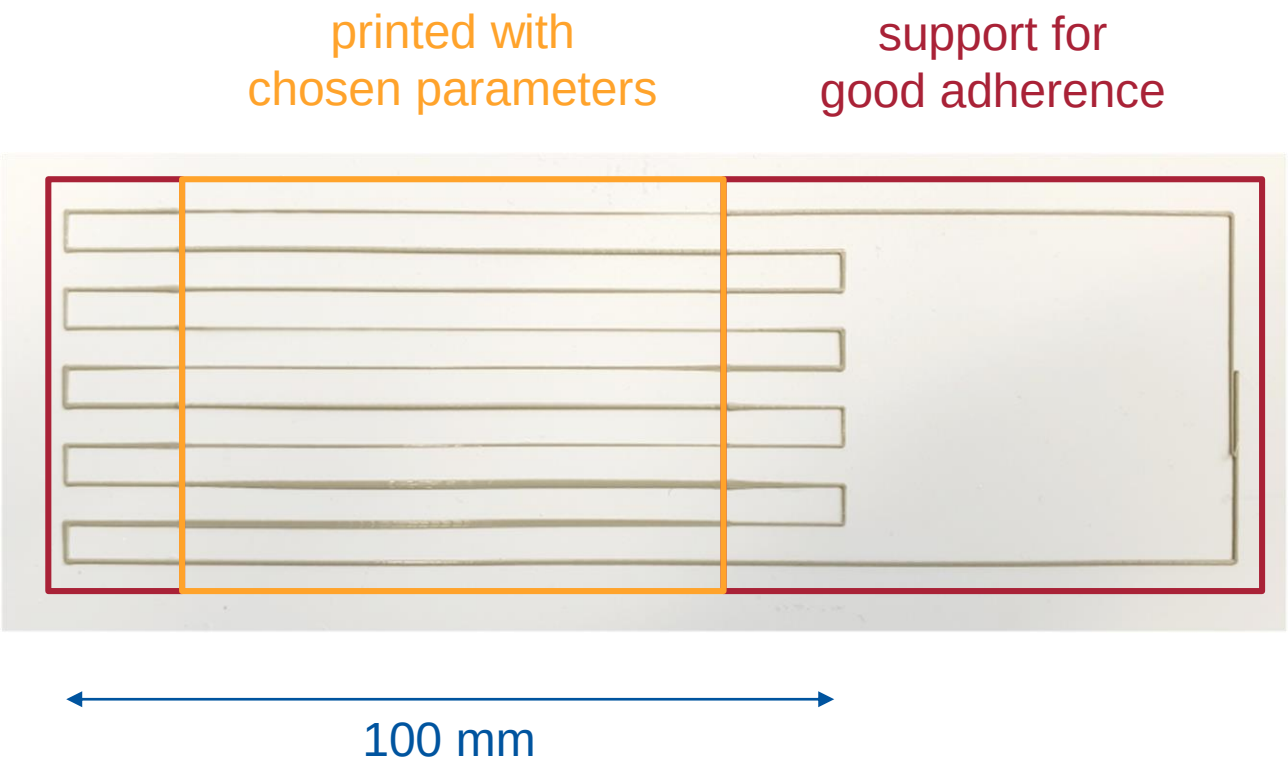


- Adjustments to the experimental setup
  - Stiffer mount for the LLS sensors with new positioning
  - New calibration routine (described in detail in the submitted abstract)
  - Integration of magnetic tape encoders for precise sensor tracking
  - Replacement of print plate by matte spray painted glass plate



- Design of experiments
  - Full factorial
  - Two levels with central point
  - Evaluated print parameters:
    - Filament feed rate in mm / mm (filament / print vector length)
    - Linear print speed in mm / s
    - Distance of nozzle to print plate in mm
    - Nozzle temperature in °C (blocking due to experimental limitations)

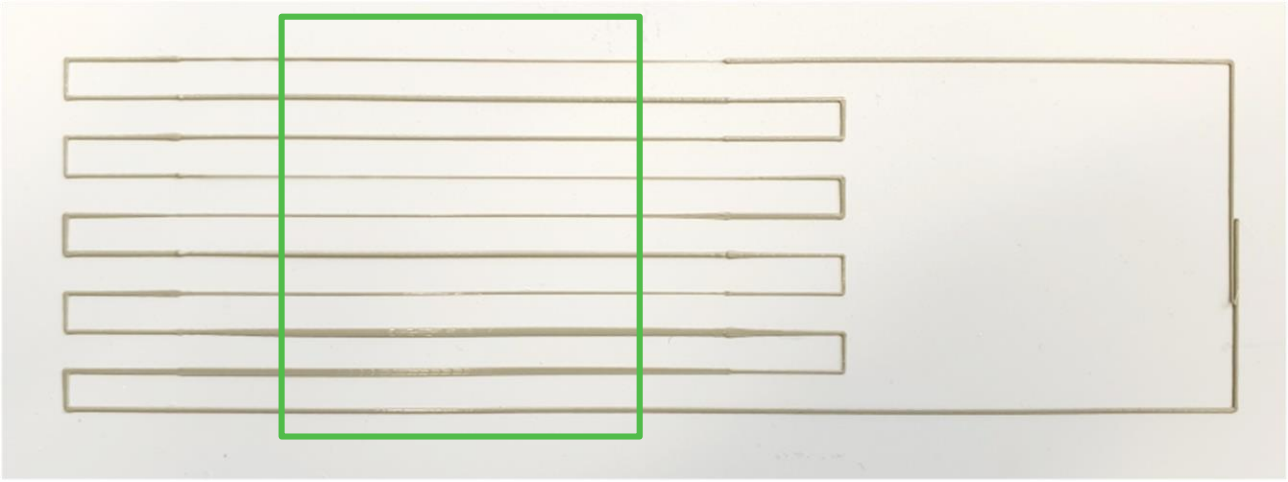
Methods – Print strategy



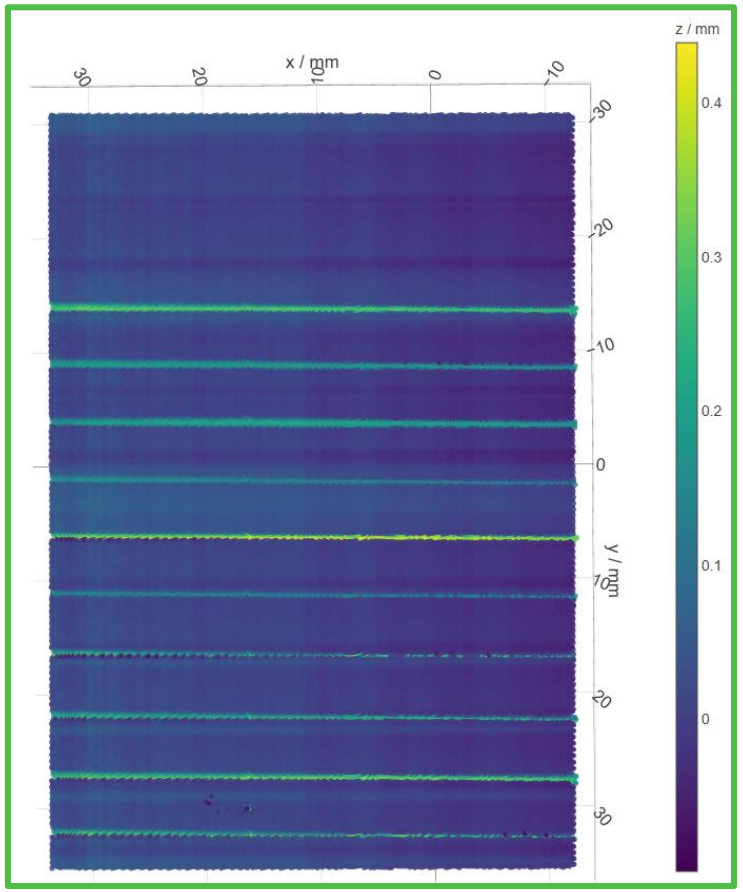
- Supporting print structure to garantee successfull print, non adherent parameter sets would otherwise interfere with the print
- All print process parameter variations (except temperature) in one print run
- Due to limitations of the used printer, the nozzle temperature can not be changed during the print process, each full run is printed with different temperatures
- 70 mm linear vectors with the chosen print parameters
- Only ~45 mm in the center will be scanned to garantee stable print conditions

Methods – Laser scanning

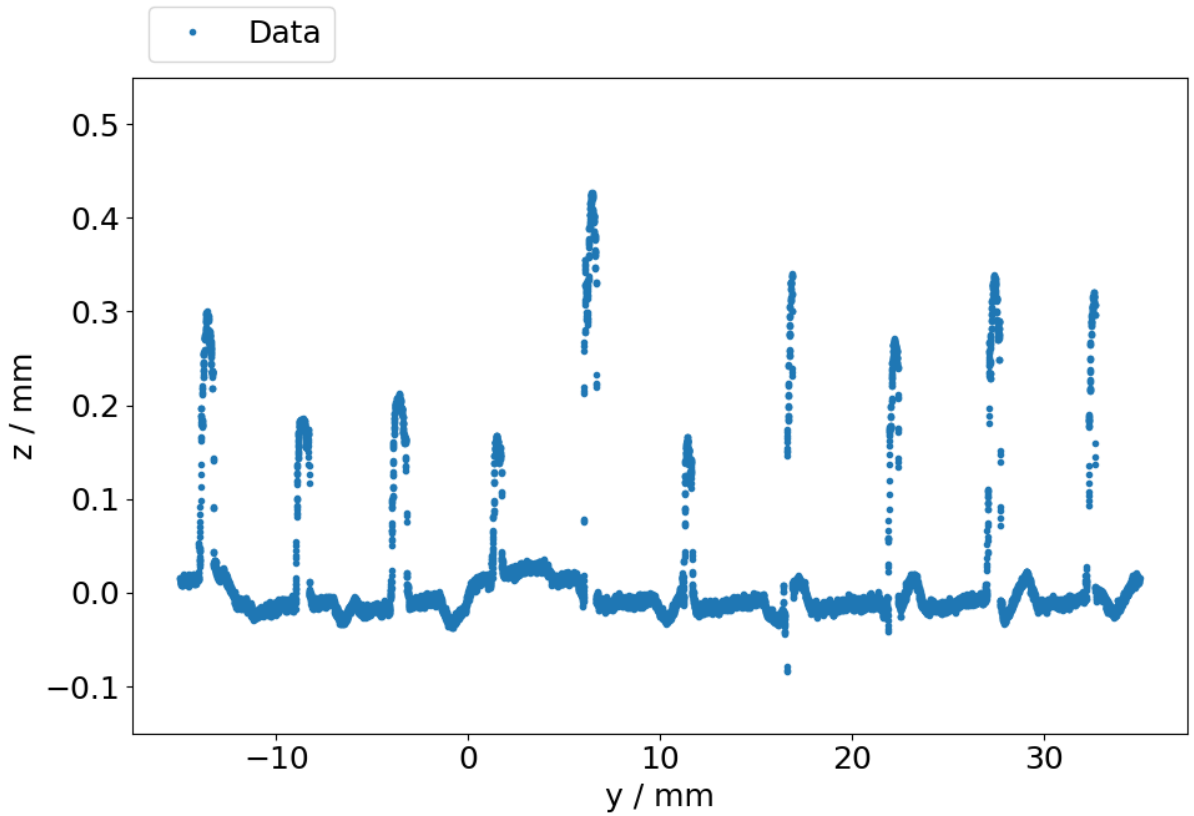
Scanned with laser line triangulation sensors

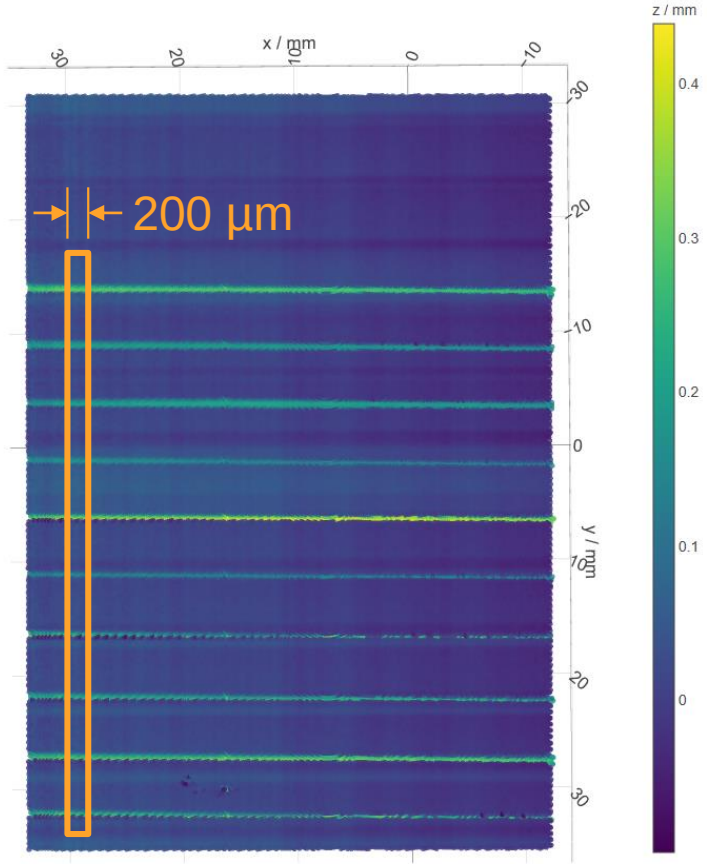


100 mm



Methods – Data segmentation





- Data points in a slice of 200 µm width in the x-axis are taken and projected to the y-z-plane
- Distance in x between data points is ~50 µm

Methods – Peak finding

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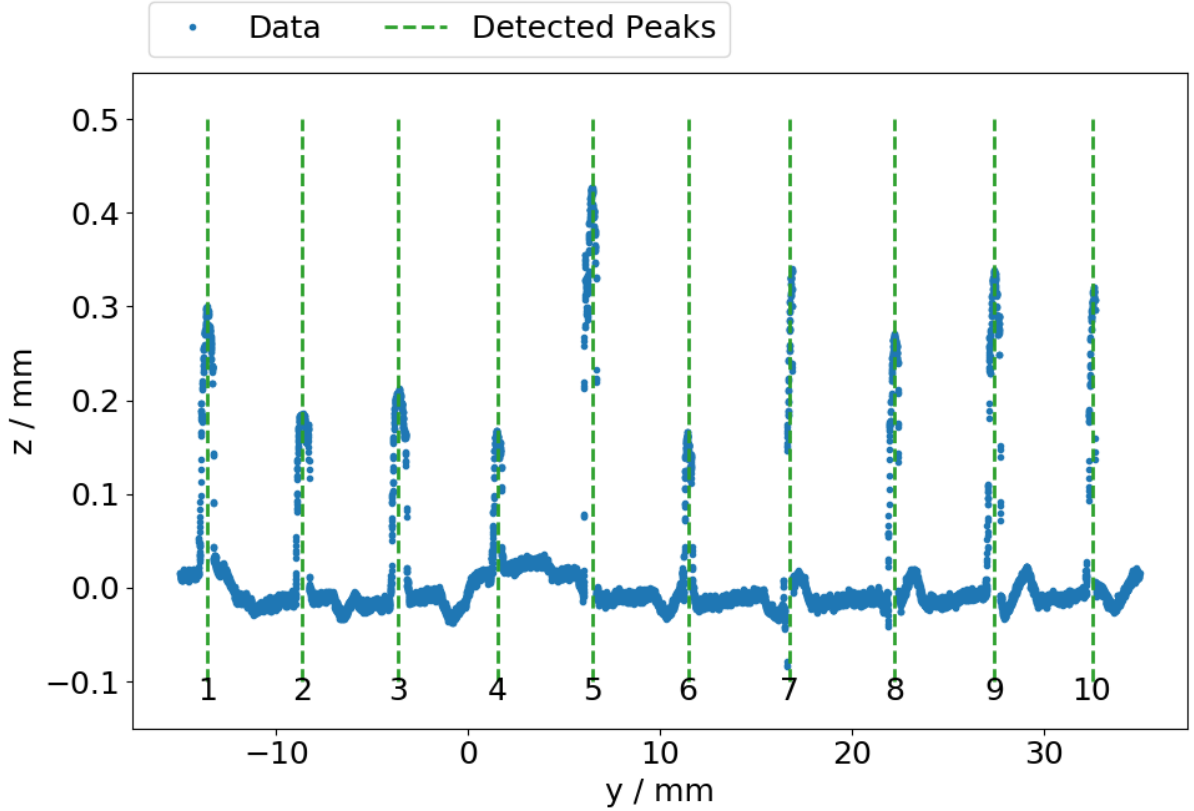

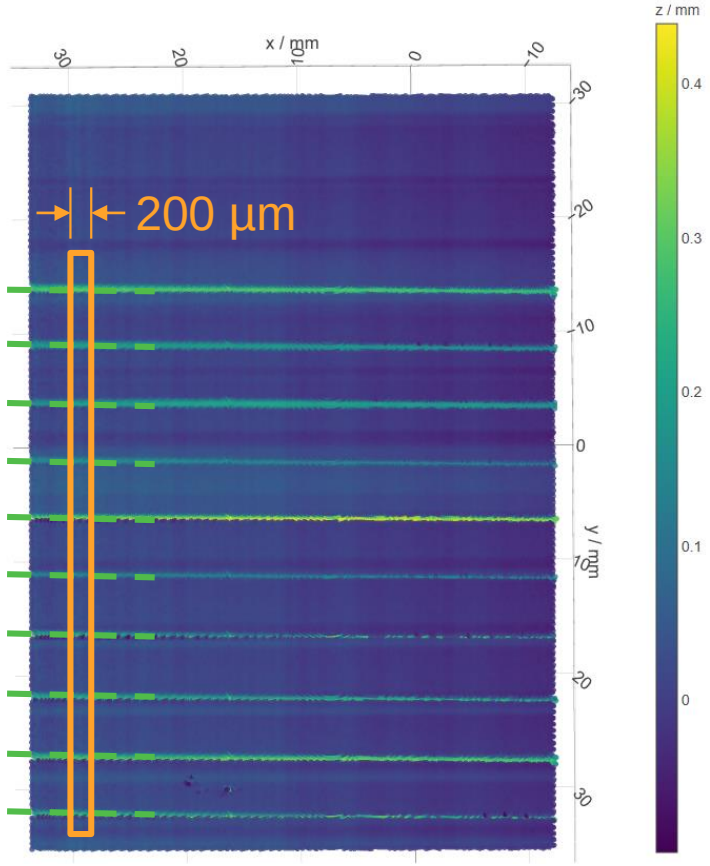

- Whole slice is cut into multiple bins
- Moving average finds area with highest z values

Methods – Sampling

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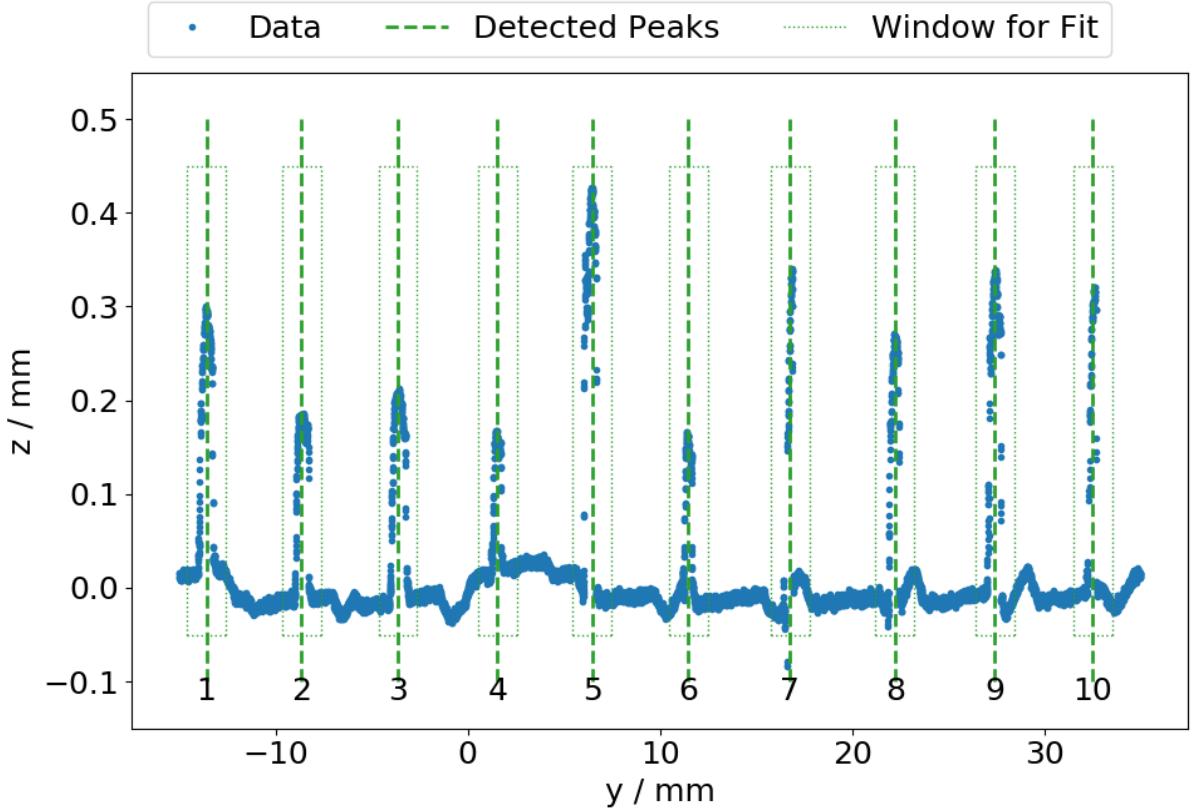

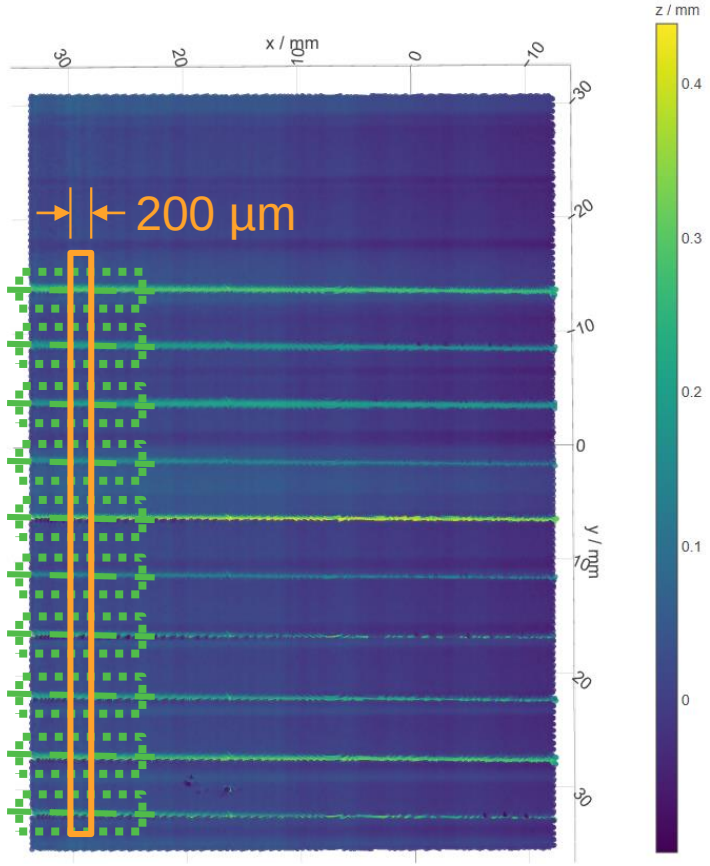

- Data points within a margin (±1 mm) around each of the found peaks are extracted separately for the analyzis of the filament shape

Methods – Repetition

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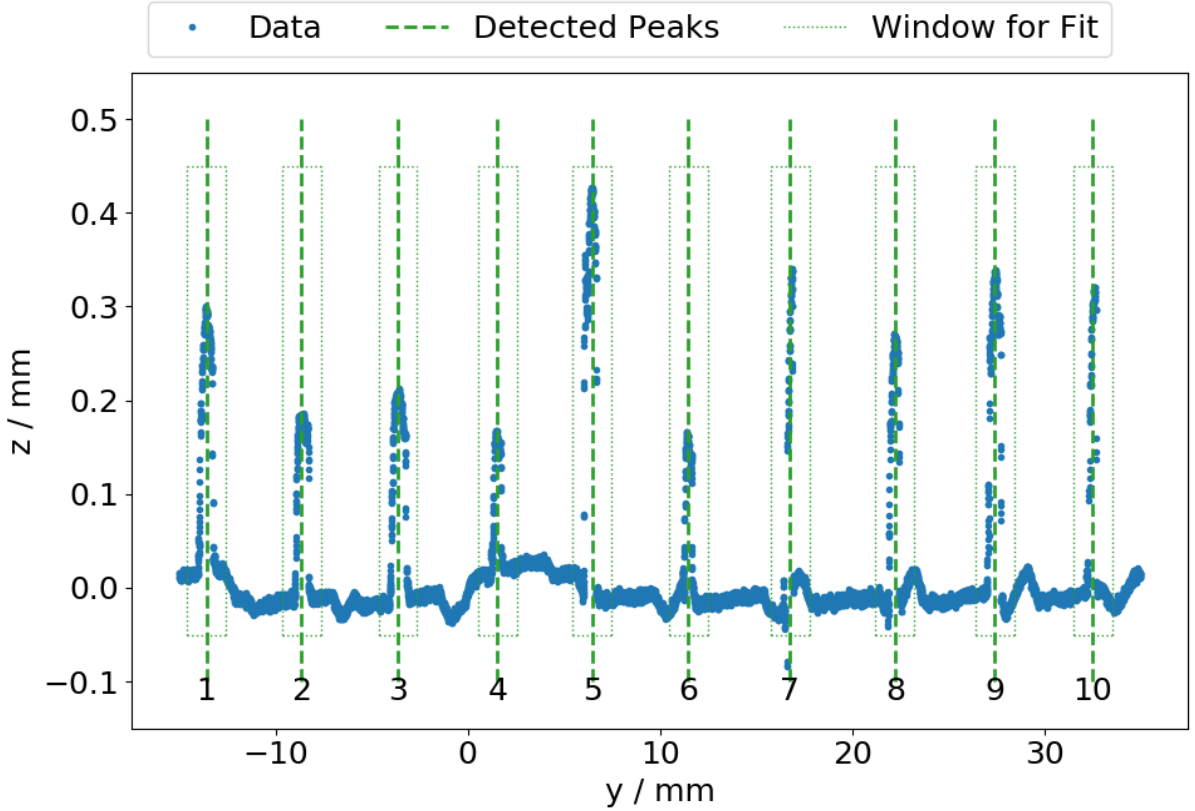

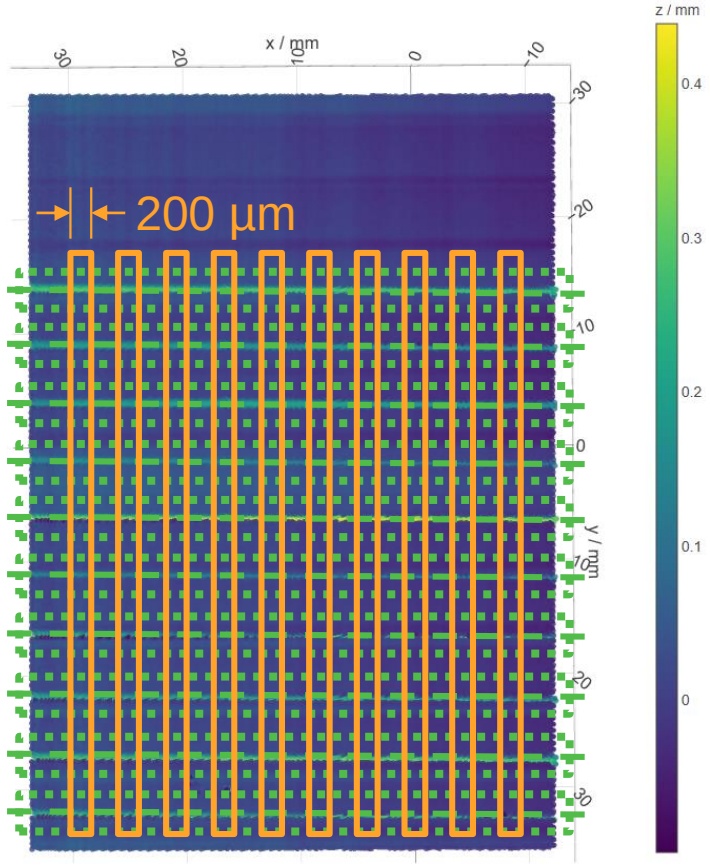

- Procedure is repeated 10 times for different positions along the x-axis
- Fit parameters are averaged over positions in x

Major findings – Example profiles

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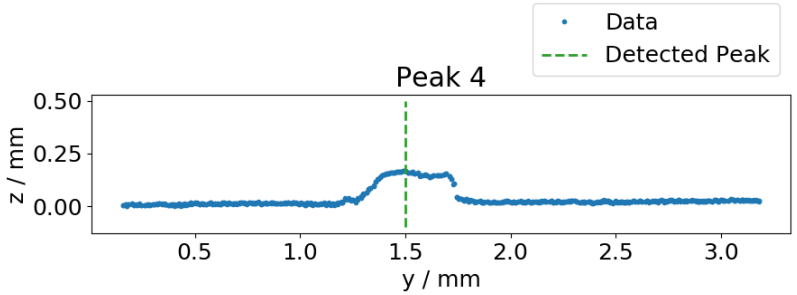

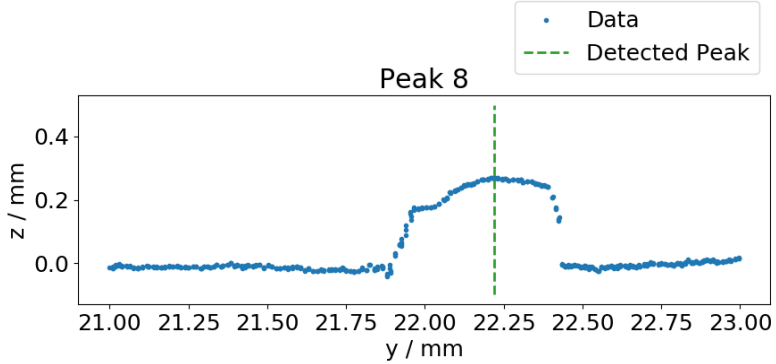

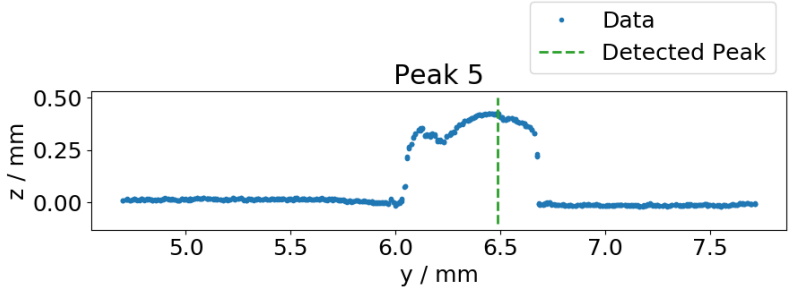

Peak	Temp. in °C	Flow Rate in mm/mm	Layer Height in mm	Print Speed in mm/s
2	205	3,326	0,1	5
3	205	3,326	0,1	305
4	**205**	**1,663**	**0,1**	**305**
5	**205**	**3,326**	**0,5**	**305**
6	205	1,663	0,1	5
7	205	1,663	0,5	5
8	**205**	**2,495**	**0,3**	**155**
9	205	3,326	0,5	5
10	205	1,663	0,5	305

Center point for flow rate based on the ratio between filament cross-section area before and after the nozzle

Major findings – Gaussian fit

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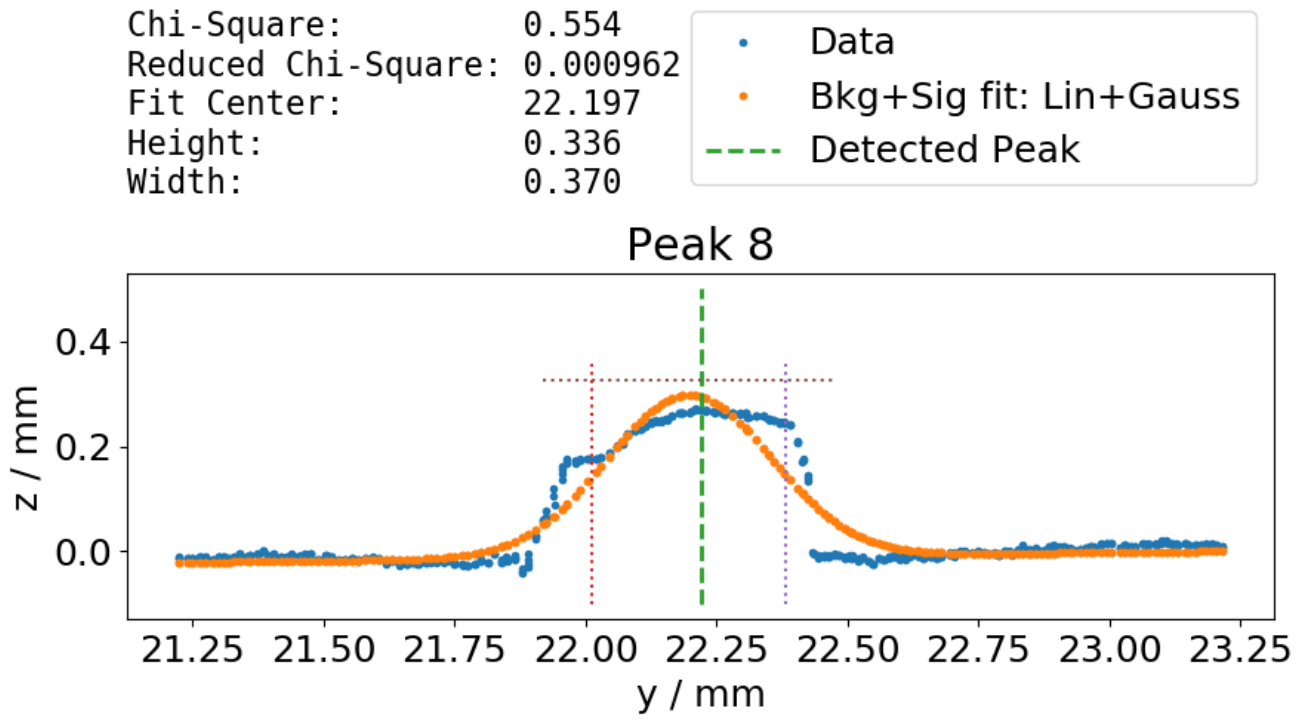

$$\frac{A}{\sigma\sqrt{2\pi}} e^{\frac{-(y-\mu)^2}{2\sigma^2}}$$

A: Amplitude
σ: Standard deviation
μ: Center of fit
y: position along y-axis

- Single fit for every x-axis position of every found peak
- Combined fit of a linear background function and a signal function
- **Height** of the filament is determined based on the **amplitude A** of the calculated fit
- **Width** of the filament is determined based on the **standard deviation σ**
- **Chi²** used as indicator for **goodness of fit**

Major findings – Rectangle & Sigmoid fit

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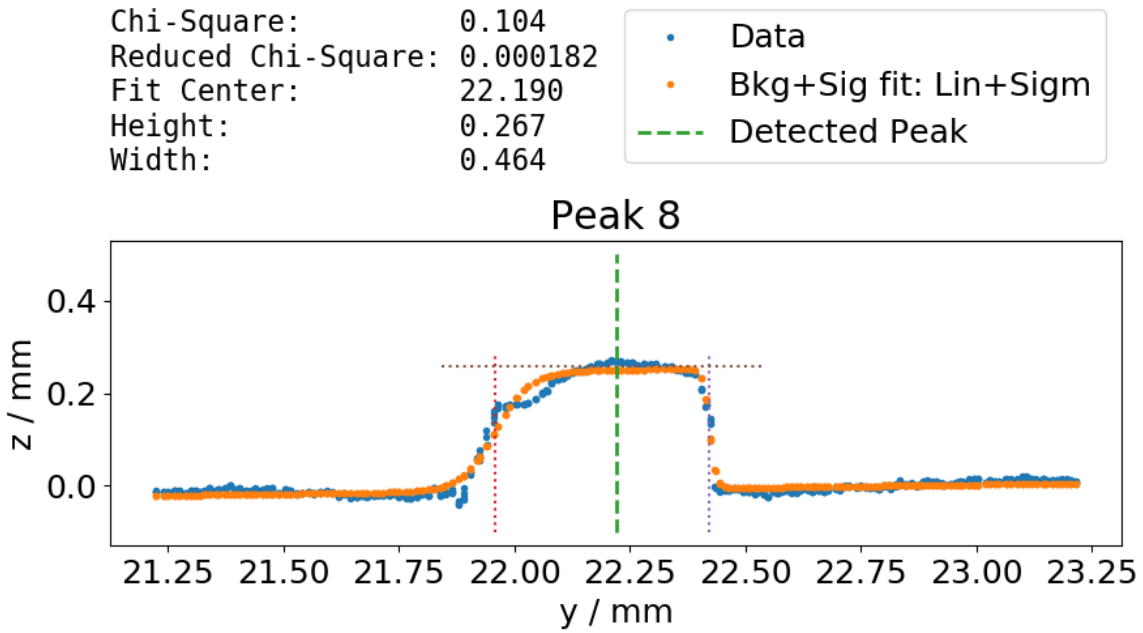

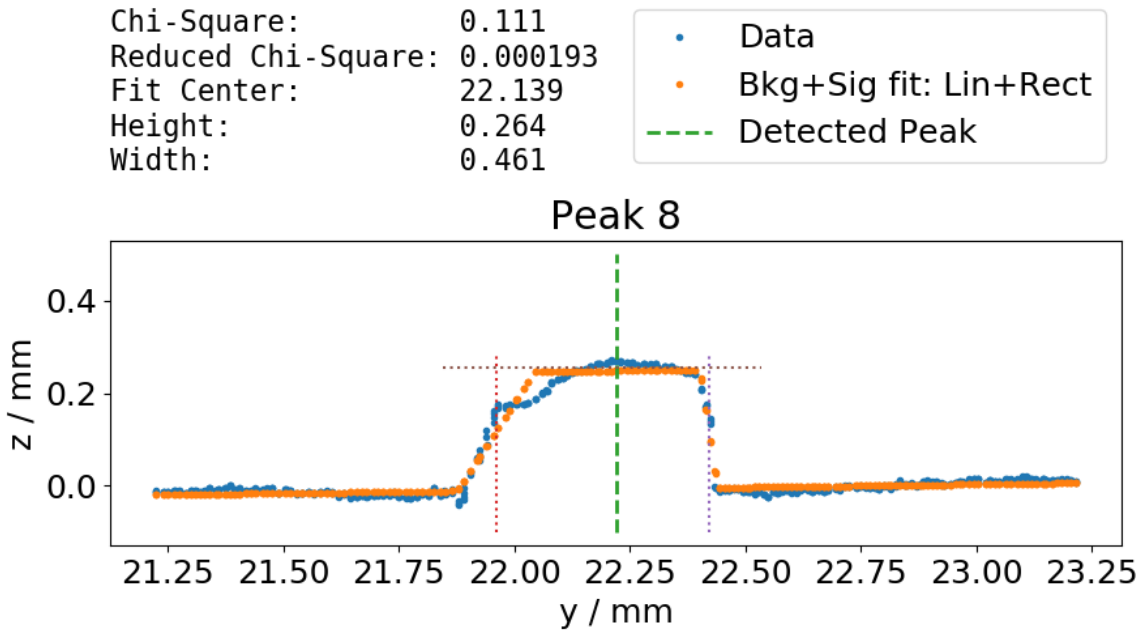

$$A \cdot \{\min[1, \max(0, \alpha_1)] + \min[-1, \max(0, \alpha_s)]\}$$

A: Amplitude
σ: Slope
μ: Center of fit
y: position along y-axis

$$A \cdot \left[1 - \frac{1}{1 + e^{\alpha_1}} - \frac{1}{1 + e^{\alpha_2}}\right]$$

$$\alpha_1 = \frac{(y - \mu_1)}{\sigma_1} \text{ and } \alpha_1 = -\frac{(y - \mu_2)}{\sigma_2}$$

Major findings – Chi square comparison

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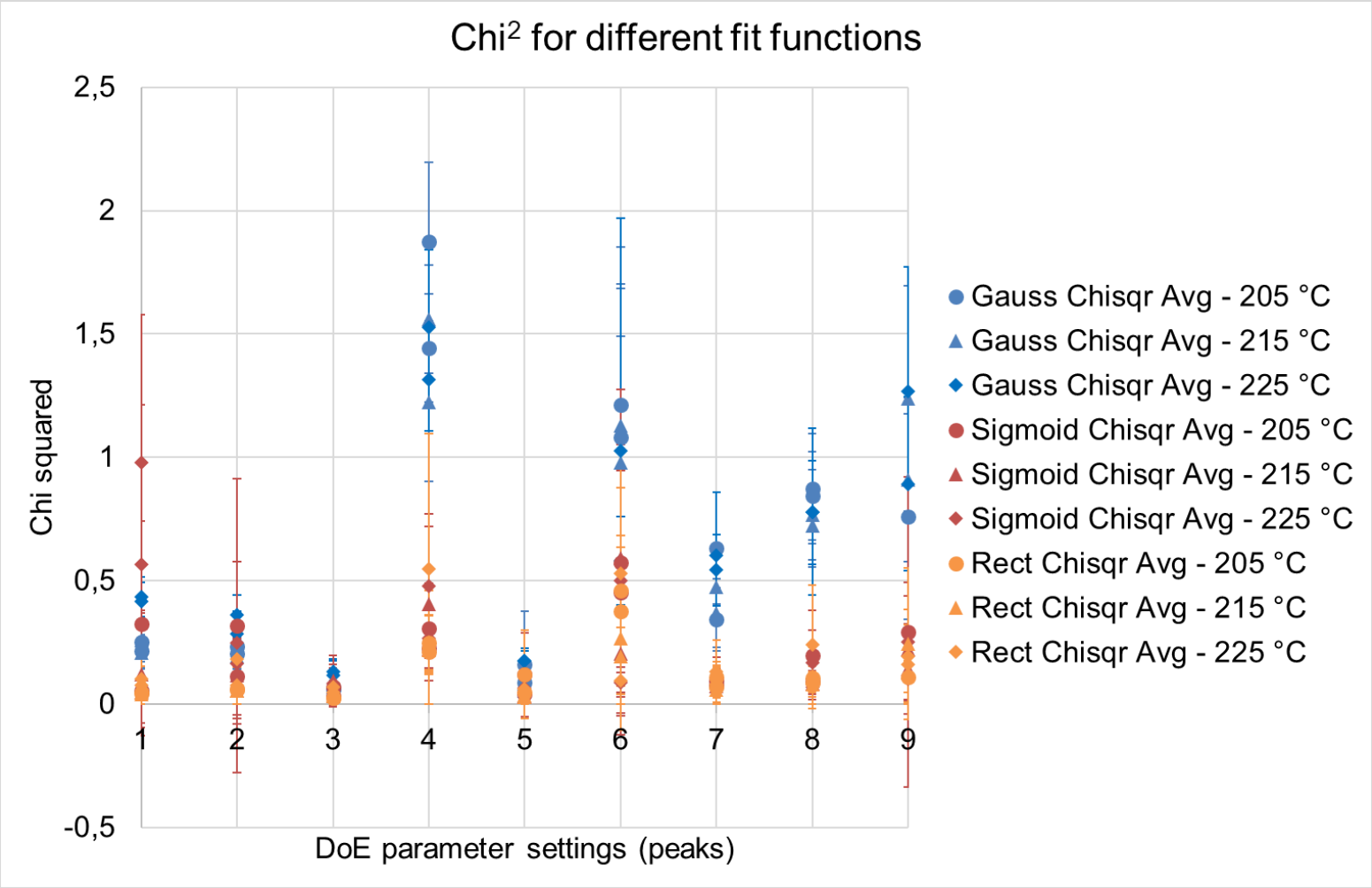
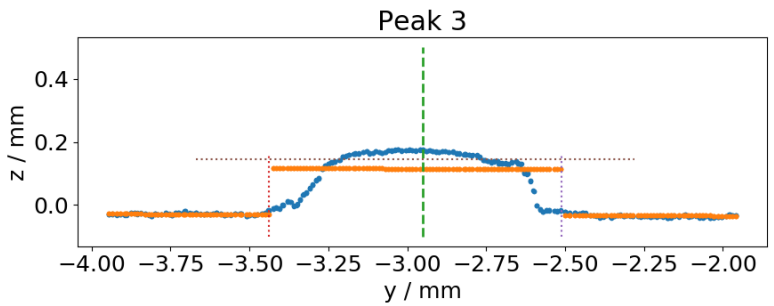


- Chi square average over all 10 x-axis positions for each peak
- Gaussian model does not provide an adequat fit
- Rectangle fit with linear slopes (trapezoid) and retangle fit with sigmoid sides provide simillar averagred chi squre values
- But sigmoid fit fails for some peaks



Conclusion

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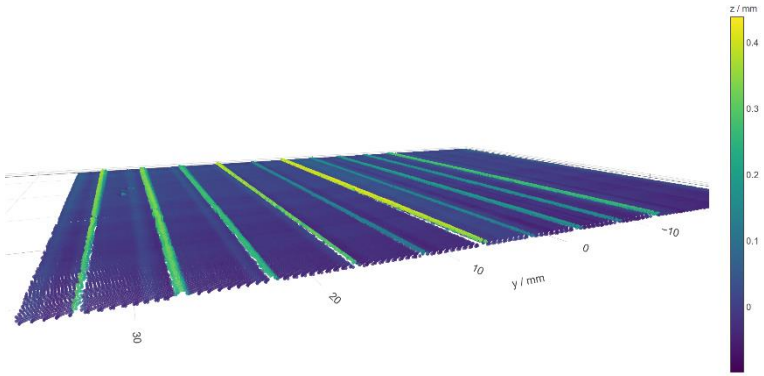

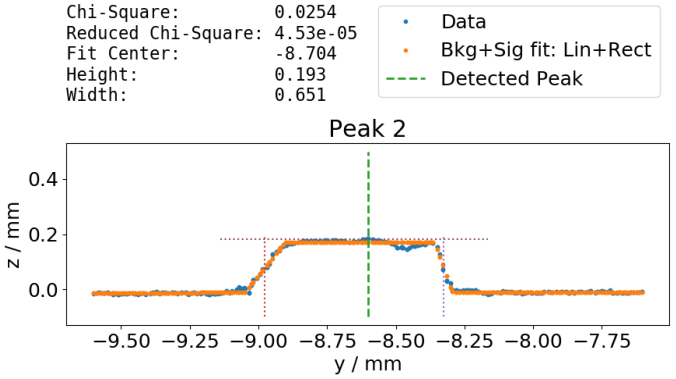

- Successfully enhanced laser line scanning system integration into a fused filament fabrication printer
- Implemented and validated new calibration routine
- Established a method to measure single printed filament lines
- Found trapezoid model to be best fit for filament shape description

Outlook

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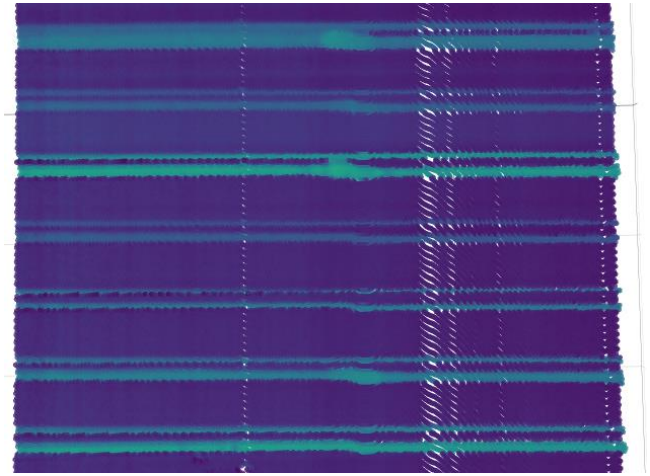

- Validate filament shape by measuring with print rotated by 90°
- Multiple lines with reducing distance between filament
- Multi-layer prints
- Integration of additional sensors
  - Optical flow sensor to track filament feed rate
  - Custom laser line triangulation scanner for true in-process measurements

Acknowledgement

DFG Deutsche Forschungsgemeinschaft
German Research Foundation

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I want to thank my co-authors and our student workers Timm Siegfried and Florian Walter.

Backup – Calibration routine

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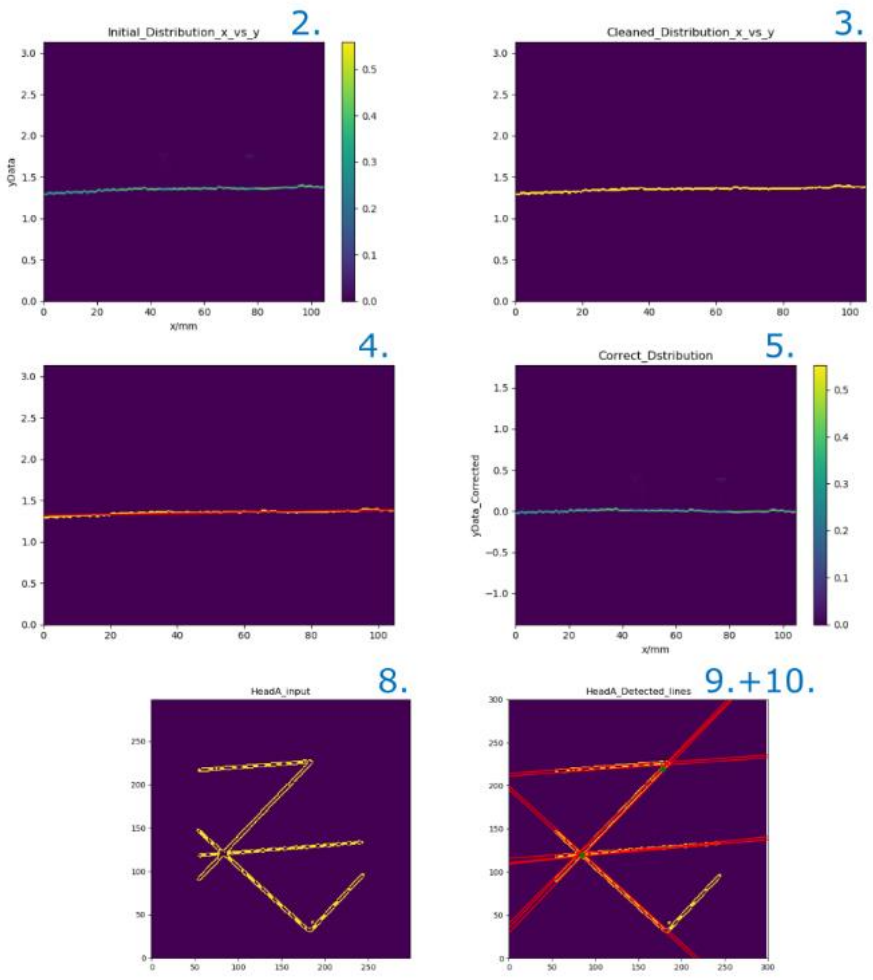

- Individually for each sensor:
  01. Segmentation between build plate and filament point clouds
  02. Projection of build plate points along the y-axis
  03. Two dimensional morphological operations to reduce noise
  04. Linear fit through the projection
  05. Rotate points along y-axis and normalize lowest point
  06. Repeat 2.-4. for rotation along x-axis
  07. Projection of filament points along z-axis
  08. Two dimensional morphological operations to reduce noise
  09. Hugh transformation to detect lines in projection
  10. Calculate intersection
  11. Cluster intersections in close proximity and remove outliers

Backup – Calibration routine

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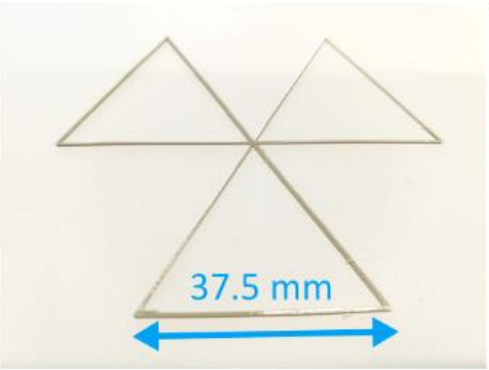

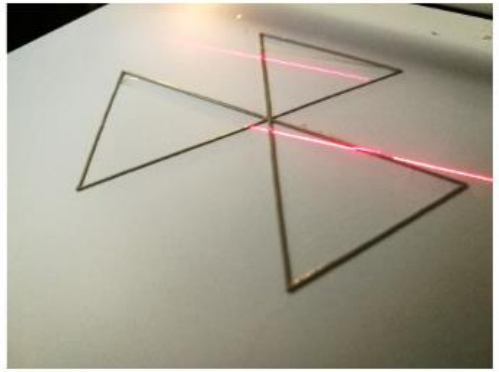

- To combine the point clouds into a single COS:
  - Match intersections
  - Select one intersection as COS-origin
  - Calculate rotation in z-axis and translation in xy-plane
  - Apply transformation to the point clouds
  - Additional rigit body fit of the point clouds

Backup – Closing gap

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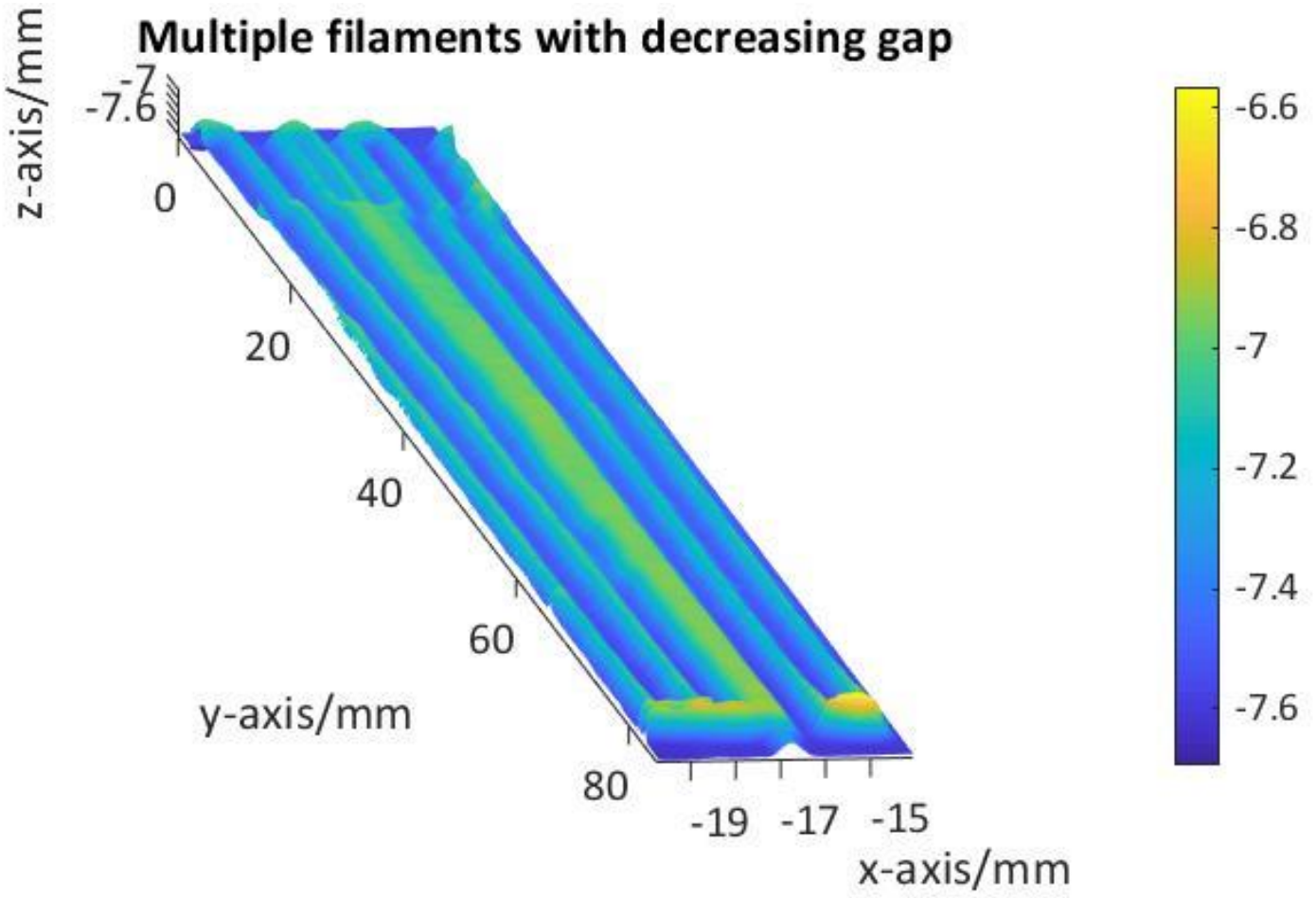

Backup – Closing gap

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