NUMERICAL SIMULATION OF AN ADDITIVE MANUFACTURING PROCESS FOR LOW-IMPEDANCE ELECTRONICS

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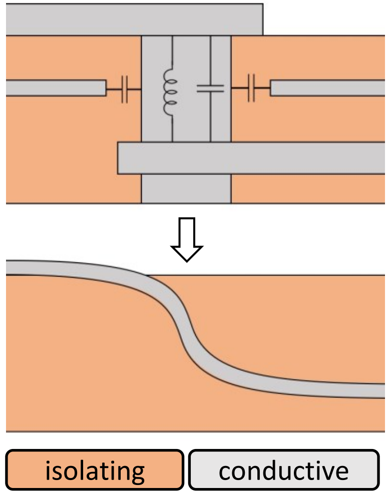
Agenda

1. What is „AM of Electronics“?

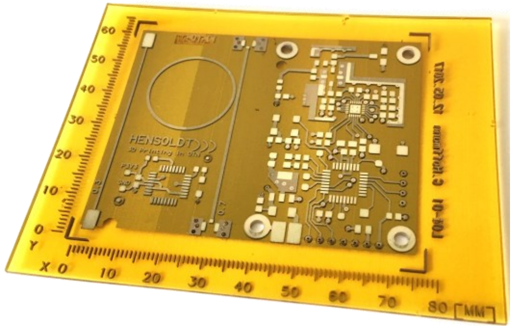
2. Current printing strategy and disadvantages for HF-applications

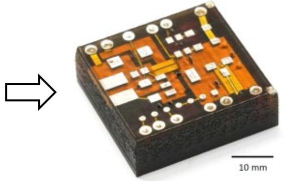
3. CFD-Simulation for optimizing the printing results

Advantages and Applications



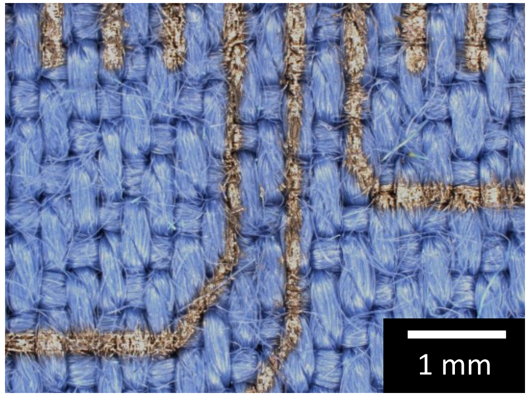
optimizing eletrical properties
e.g. avoiding losses





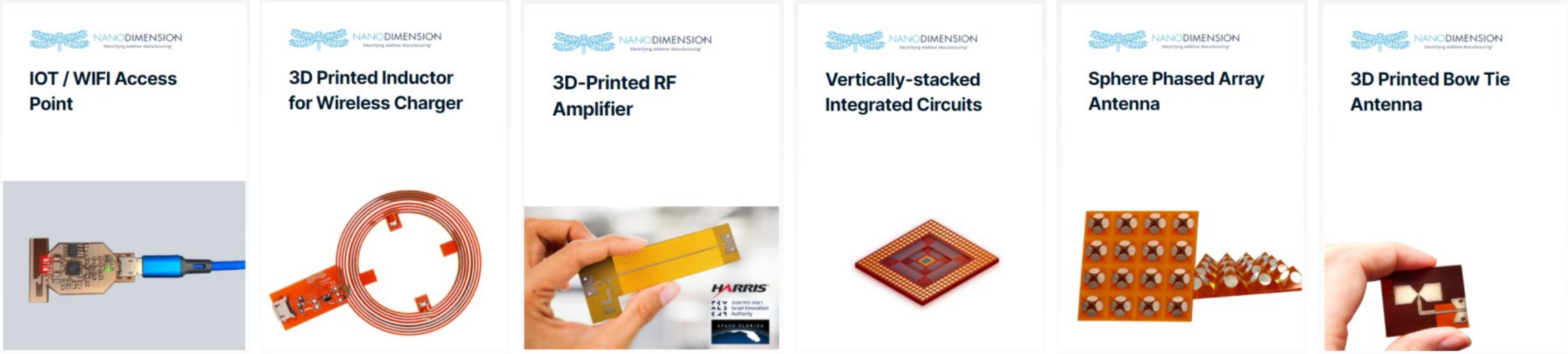
h = 9 mm
(printed by James)

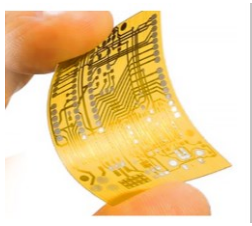
new design capabilities
e.g. miniaturization



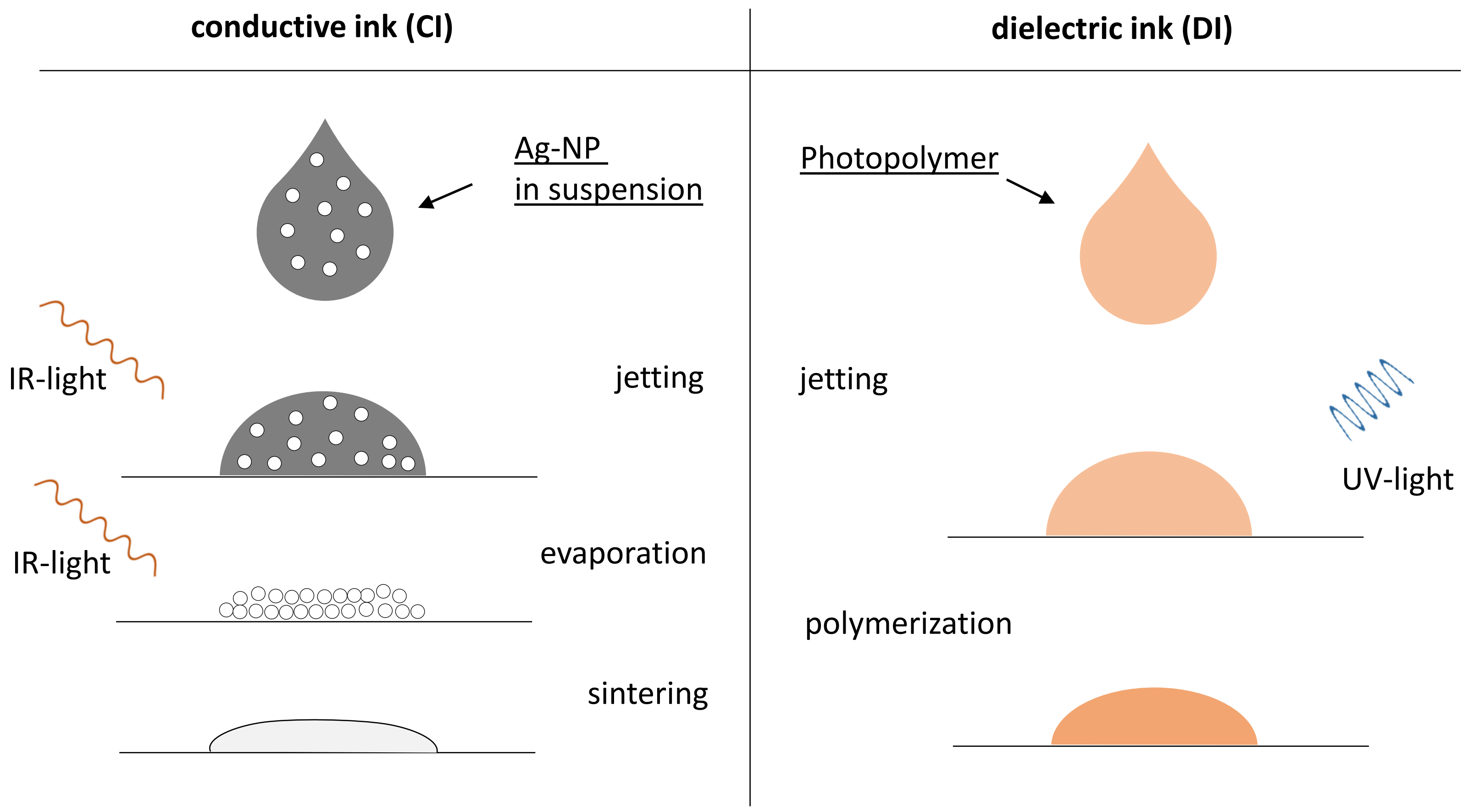
integration of functions
e.g. electrification of textiles

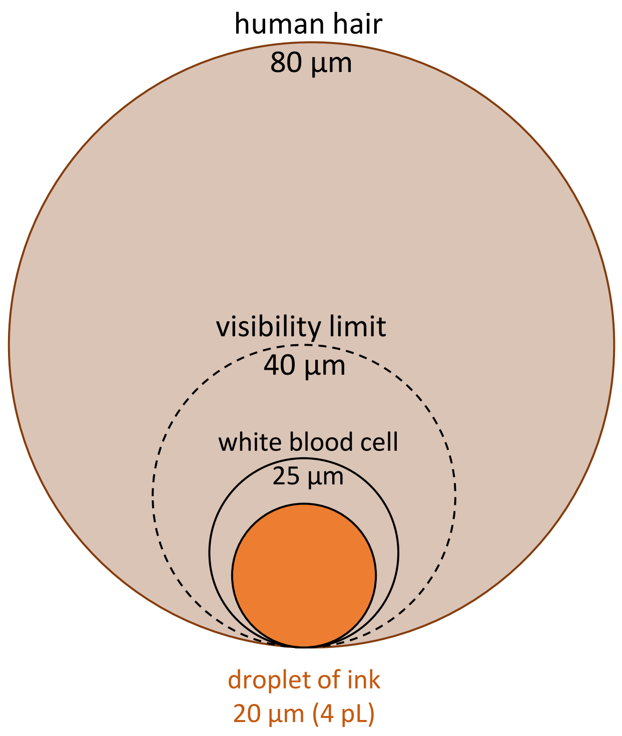
wide field of applications: antennas





3D-Printing of Electronics using material jetting



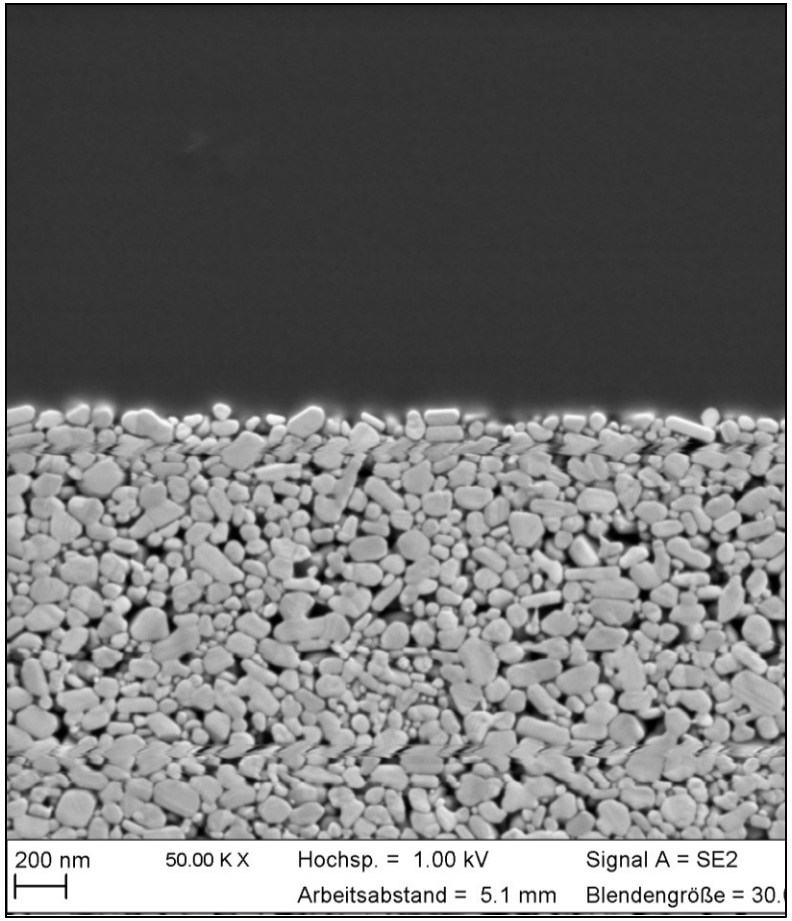


size comparison

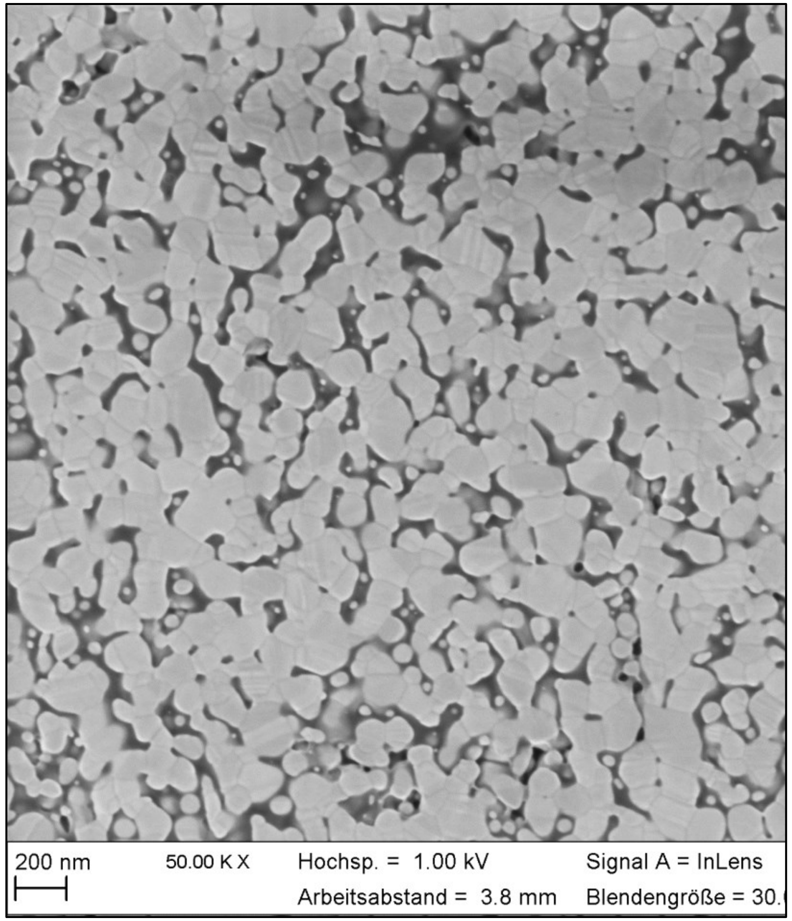
Key facts of the printing process:

nozzle frequency:	10.000 Hz	droplet volume:	4 pl
application rate:	> 10 Mio./s	droplet speed:	4 m/s
		nozzle distance:	72 µm

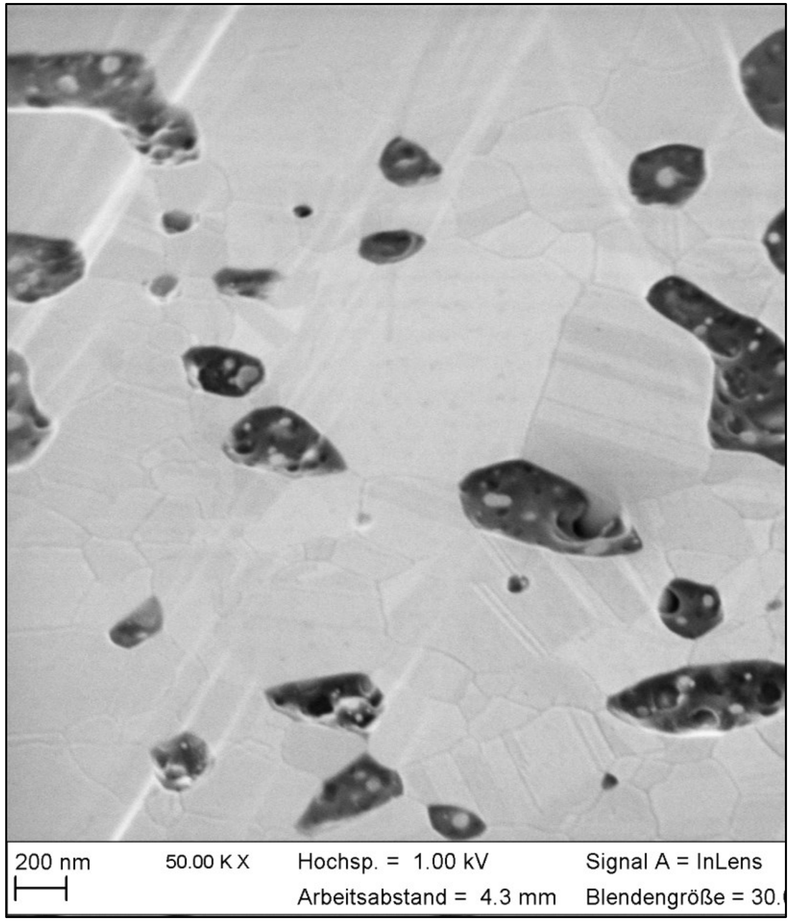
Development of the level of sintering



3 %
of bulk conductivity

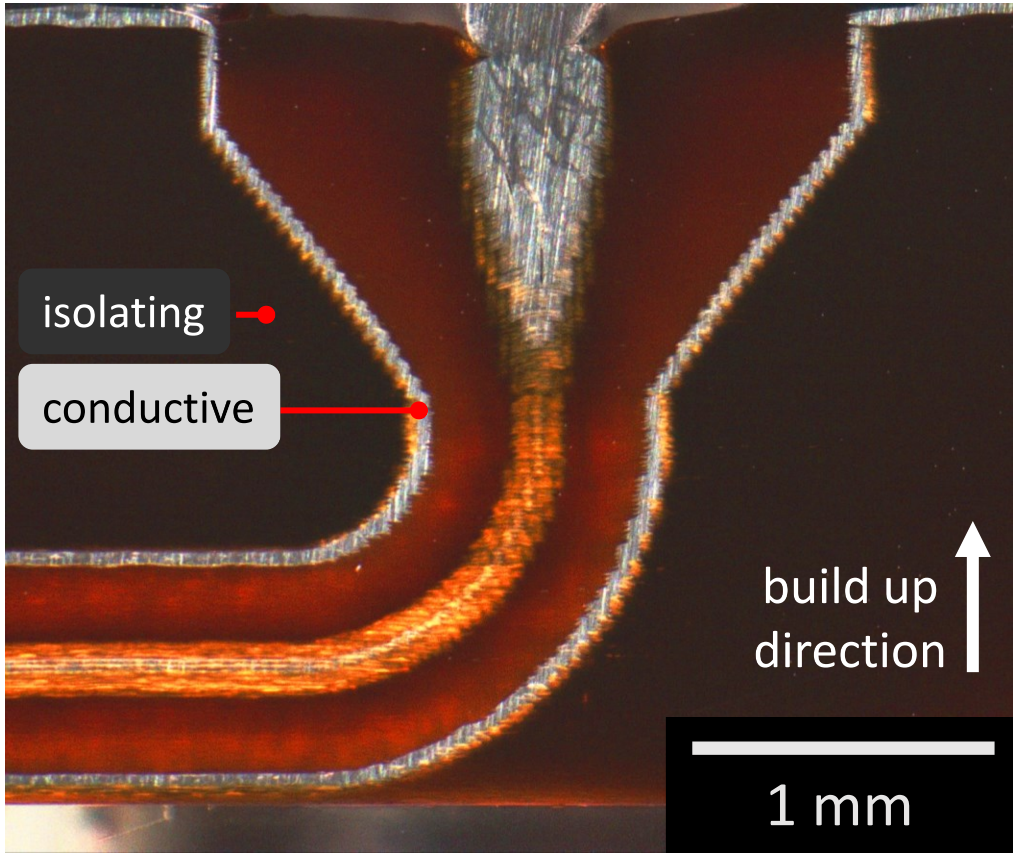


30 %
of bulk conductivity

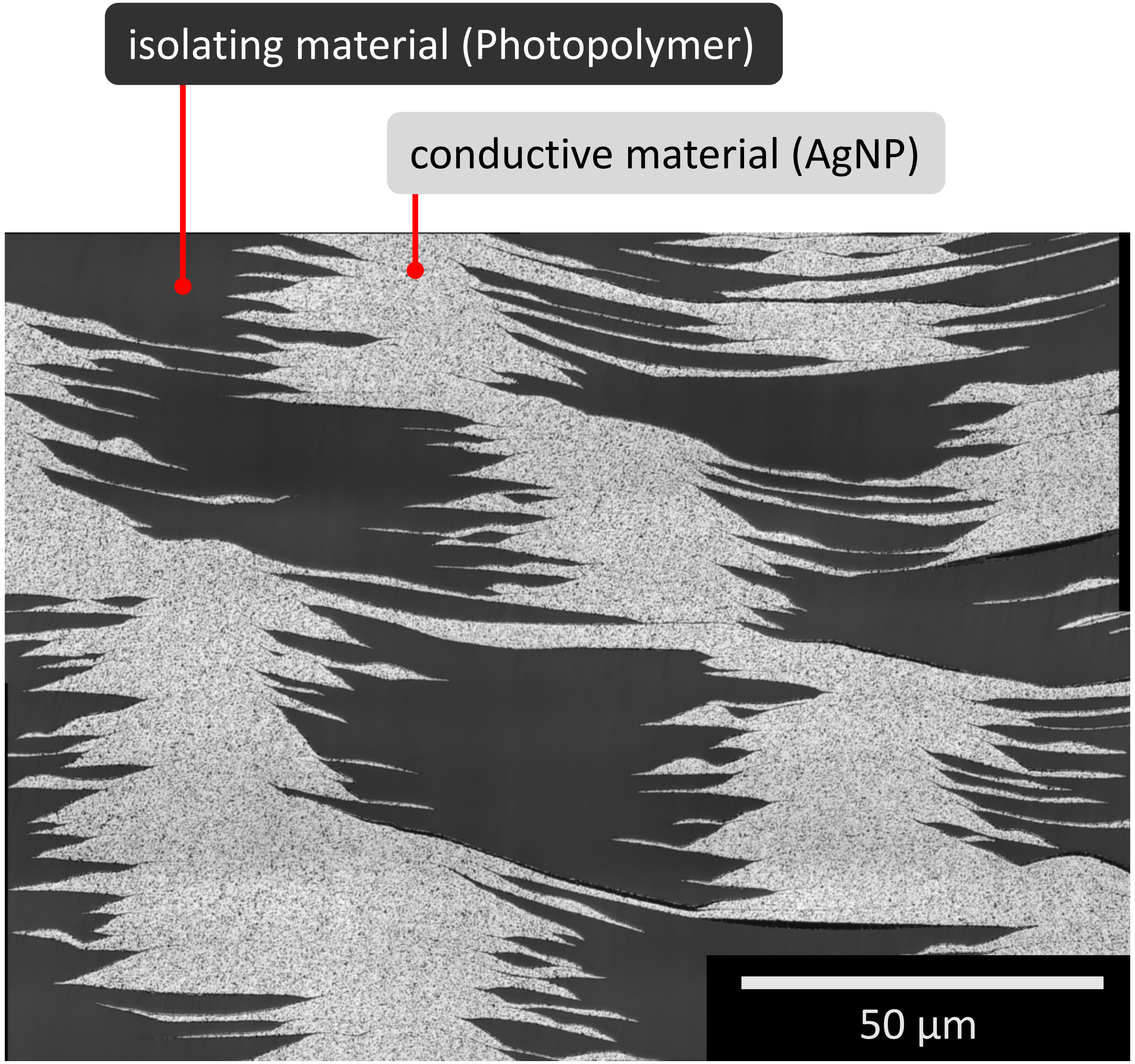


> 70 %
of bulk conductivity

A closer look to the microstructure

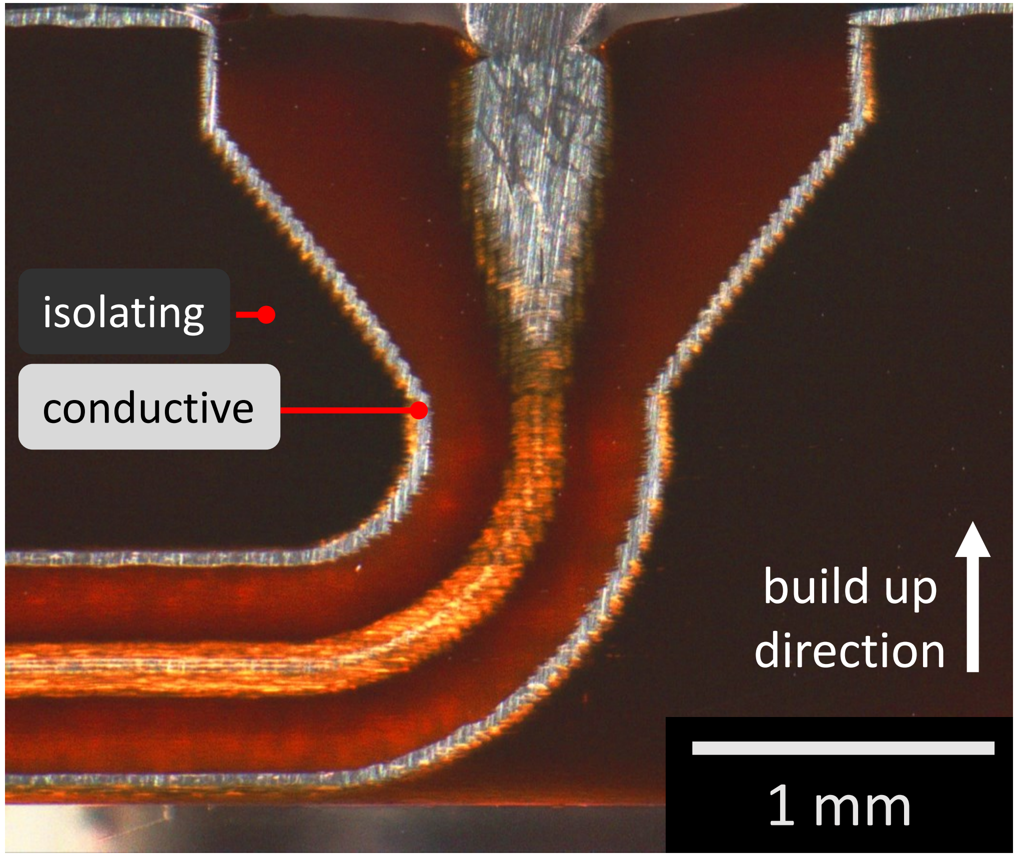


3D-printed coax line

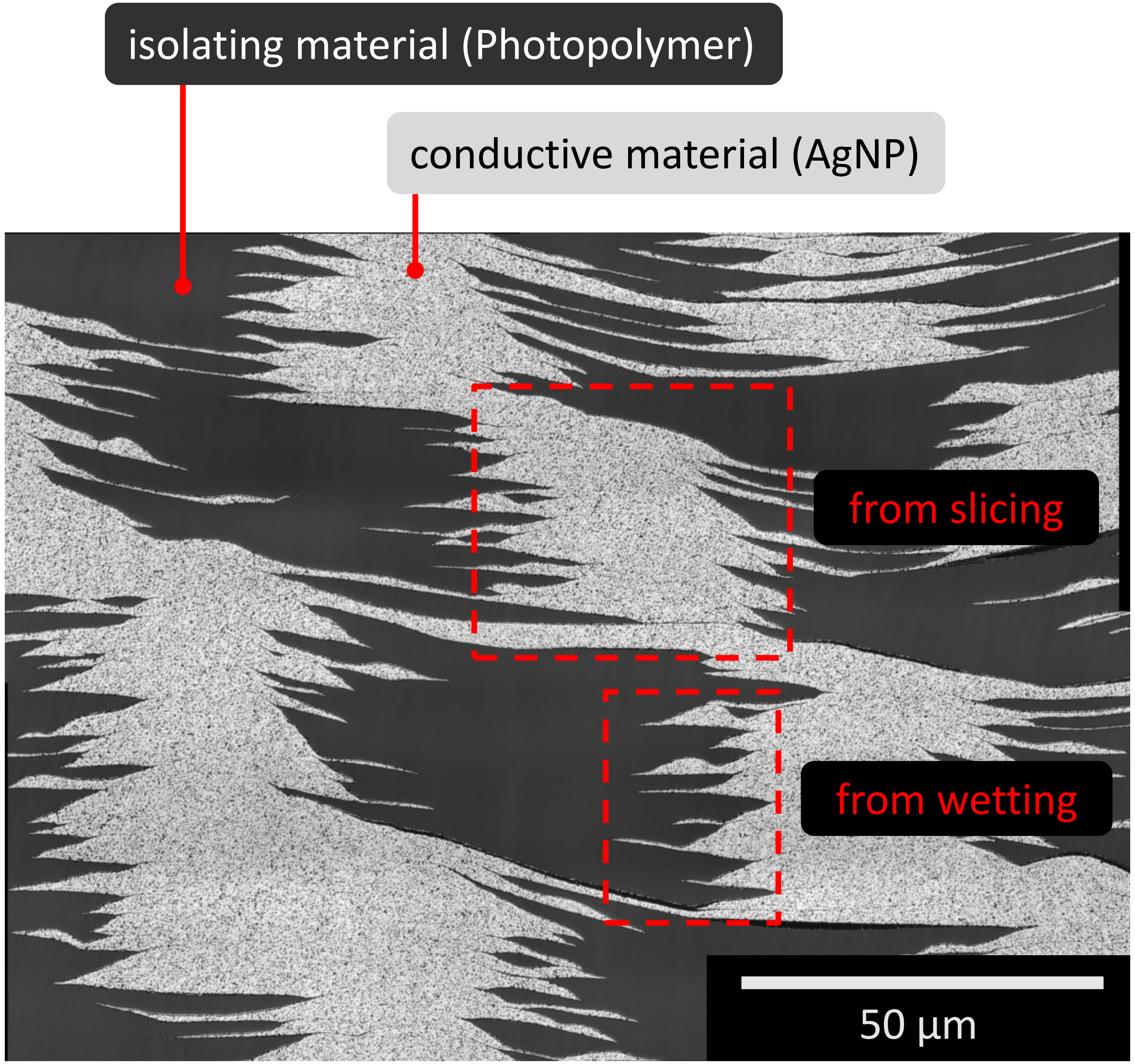


micro-structure as cross section

A closer look to the microstructure

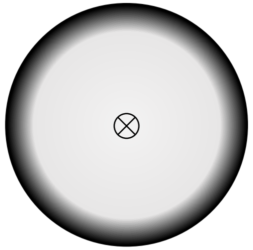


3D-printed coax line

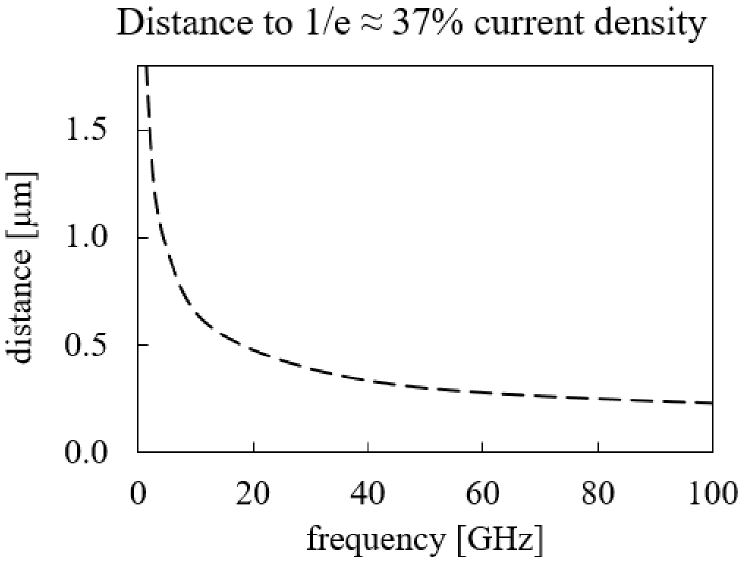


micro-structure as cross section

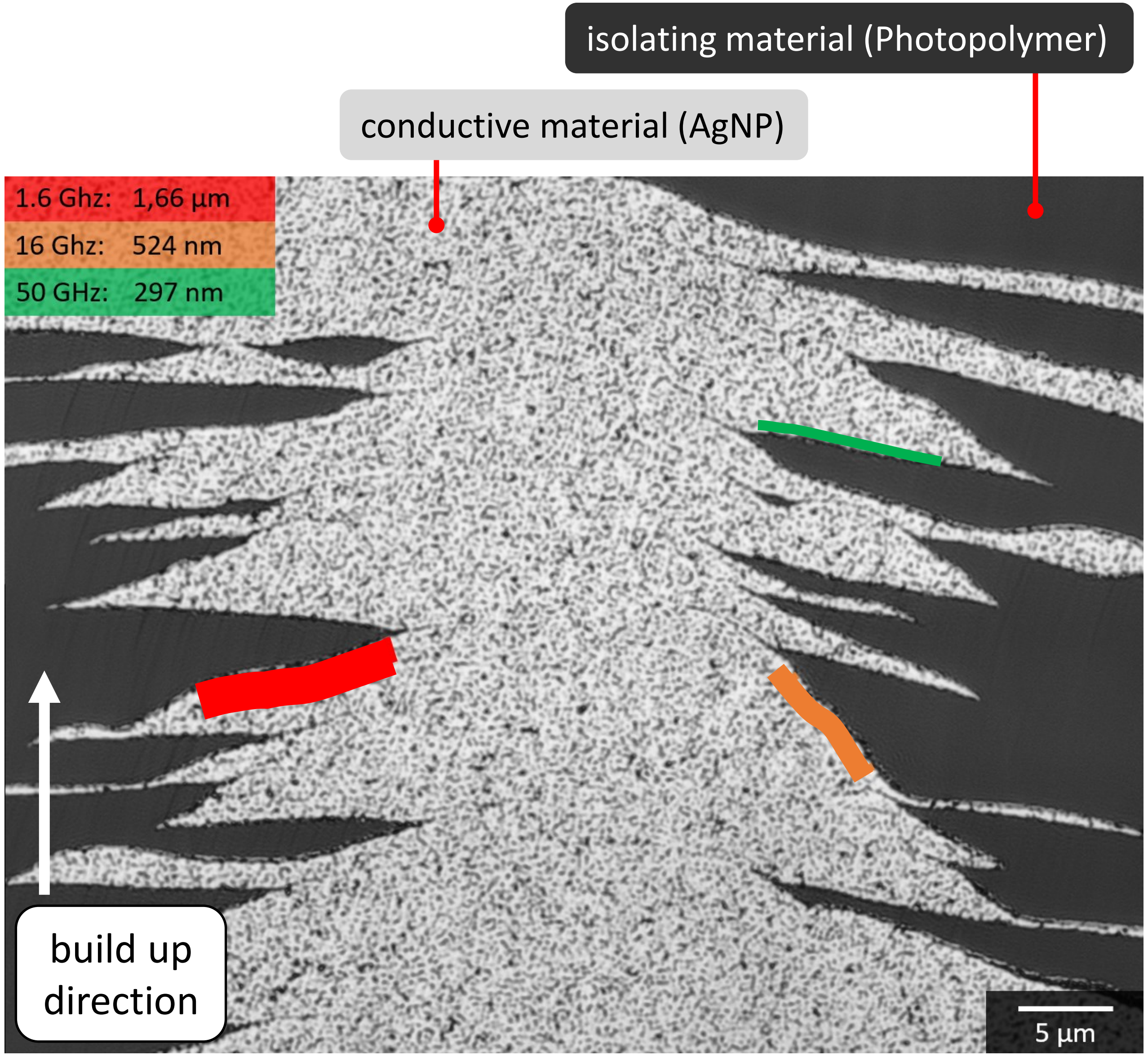
HF-properties due to Skin-Effect



schematic current density distribution due to Skin-Effect



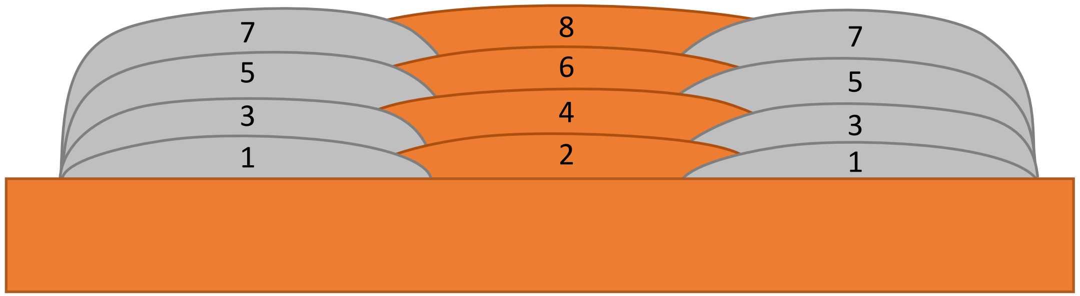
penetration depth to 37% of current density in a circular conductor due to the Skin-Effect.



Microstructure as cross section – size comparison with effective cross section area

The idea of an optimized printing strategy

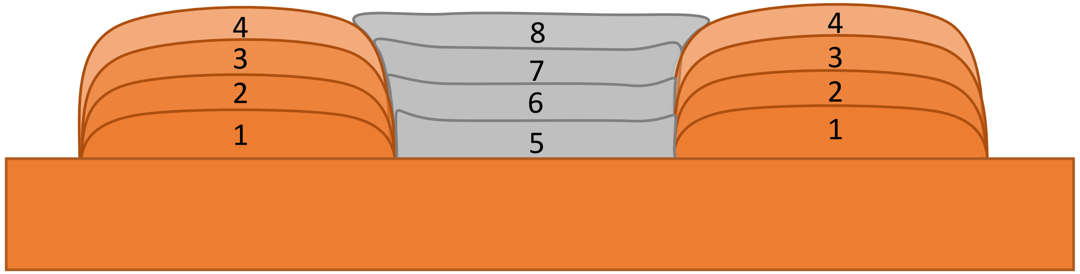
current strategy



- one layer of conductive ink
- one layer of dielectric ink

„2.5D-printing“

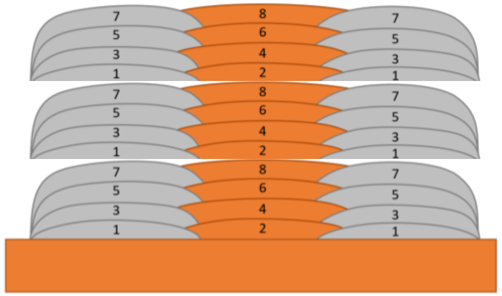
new approach

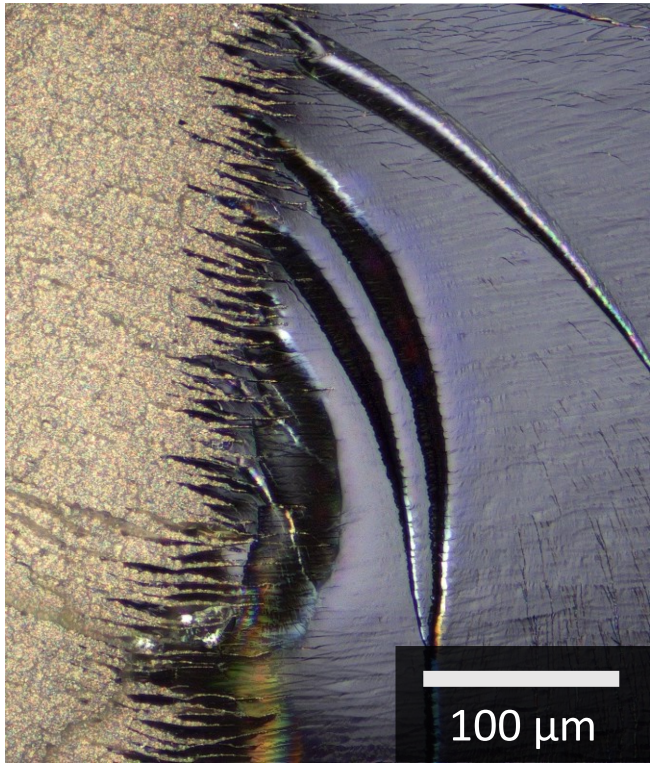


- multiple layers of of dielectric ink
- multiple layers of of conductive ink

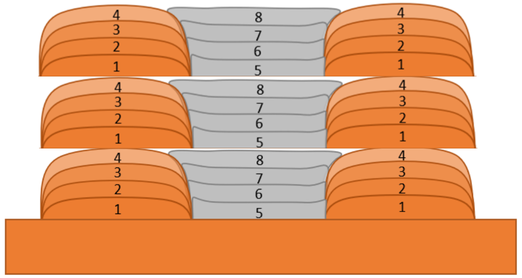
„2.75D-printing“

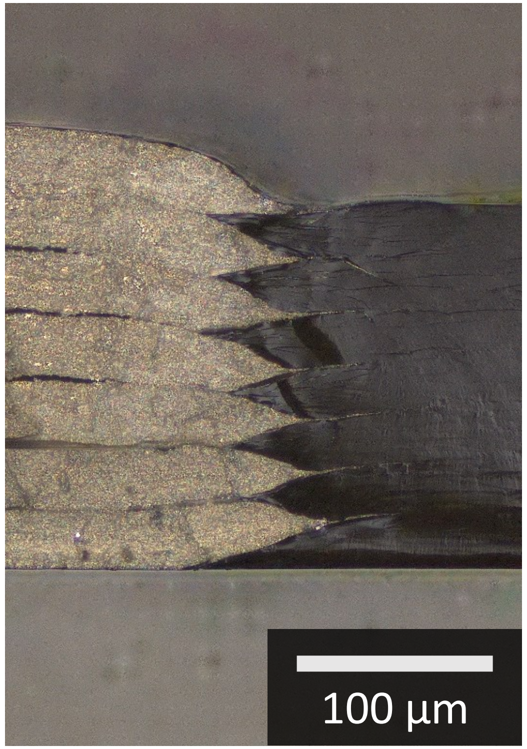
First results of printed samples using a custom slicer





microscopic picture of
***current** printing strategy*

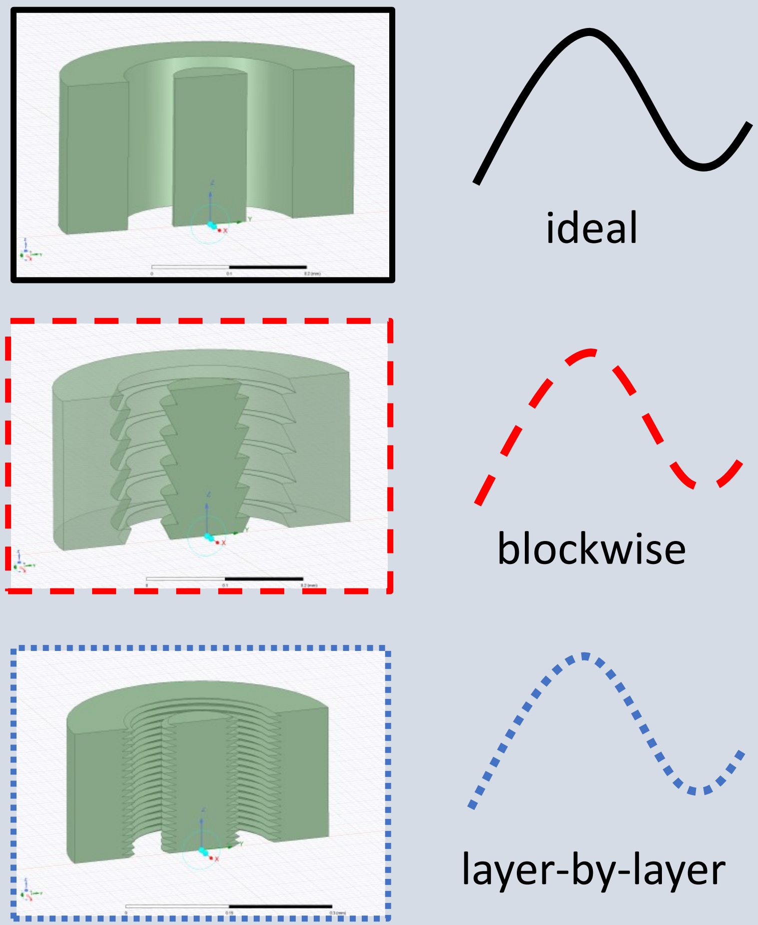




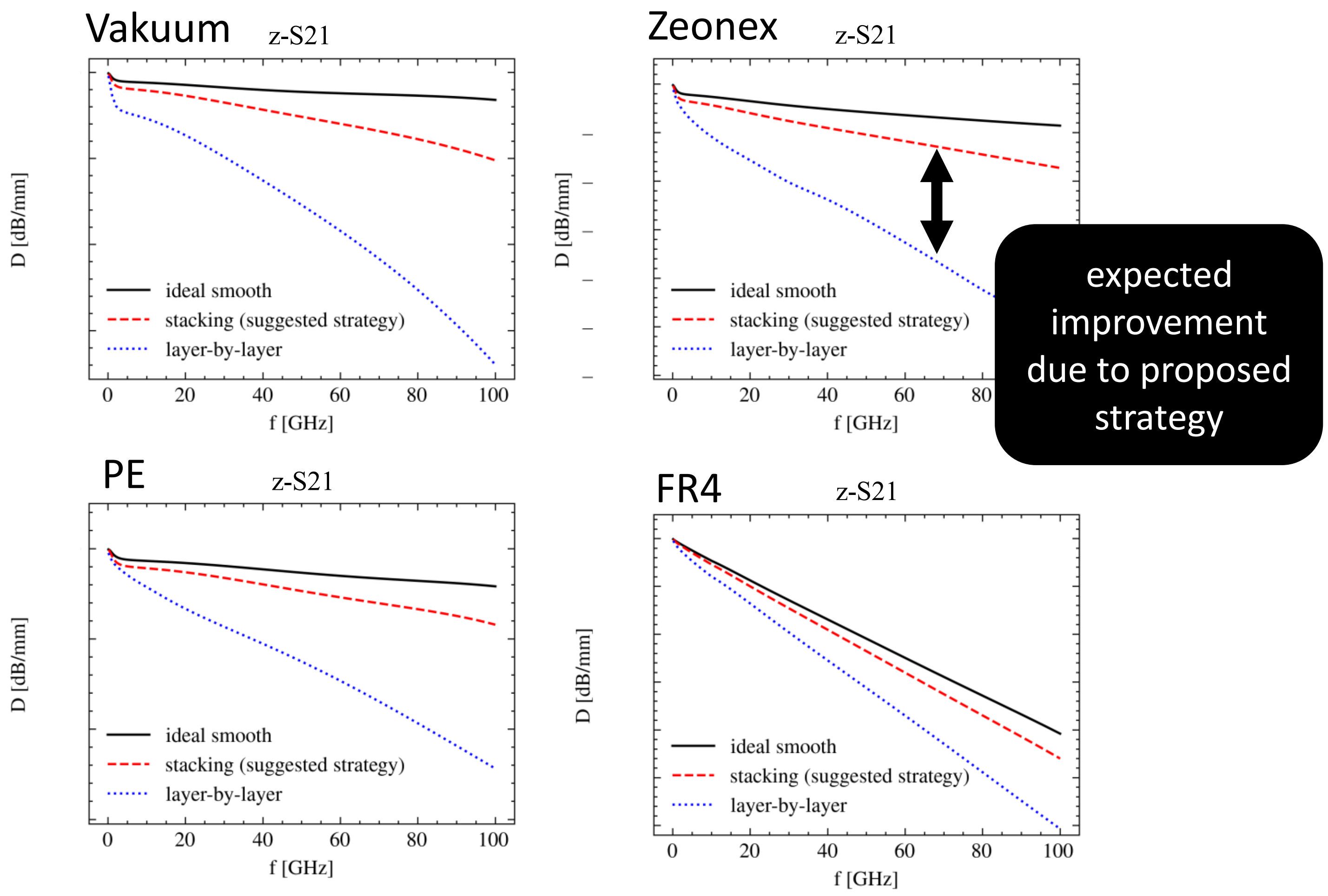
microscopic picture of
***proposed** printing strategy*

HF properties evaluation using numerical simulation

(with Ansys HFSS: high-frequency structure simulator)



simulated representative 3D-geometries for HF-simulation



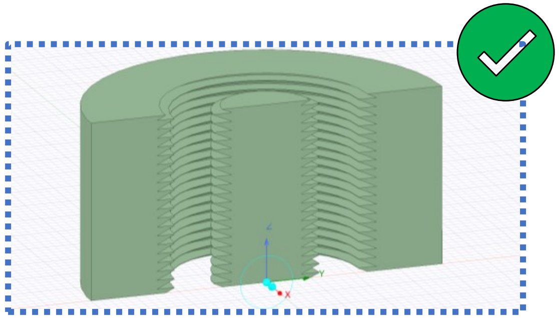
Comparison of the simulated damping characteristics (S21) for different dielectrics

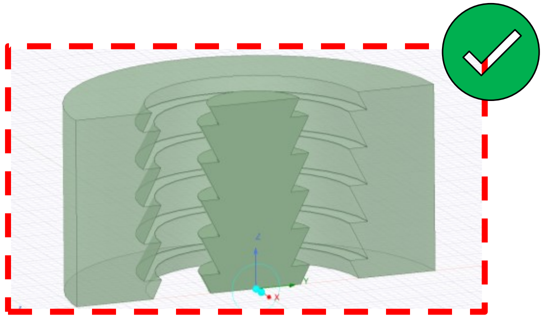
Optimizing the stacking

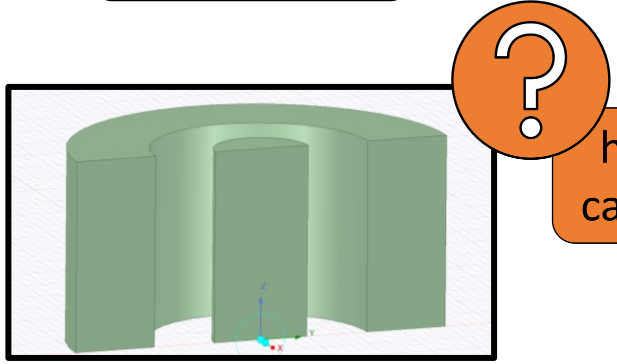
layer-by-layer

blockwise

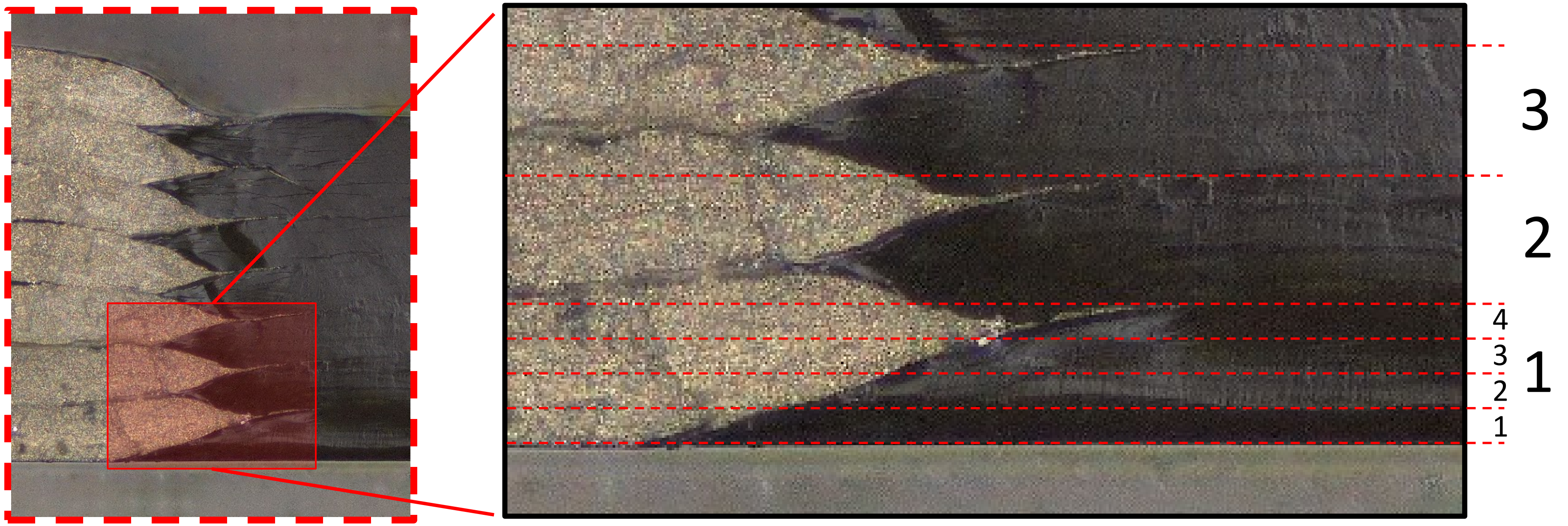
ideal





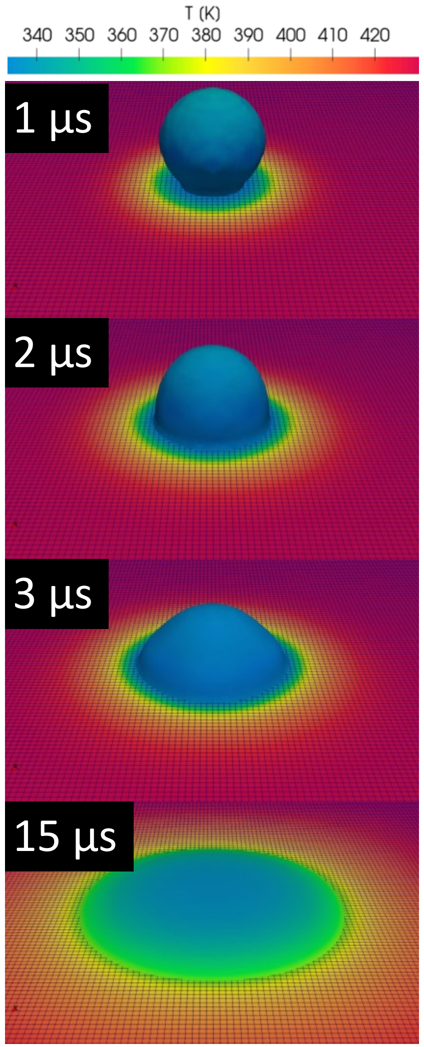


how close can we get?



Stacking of droplets

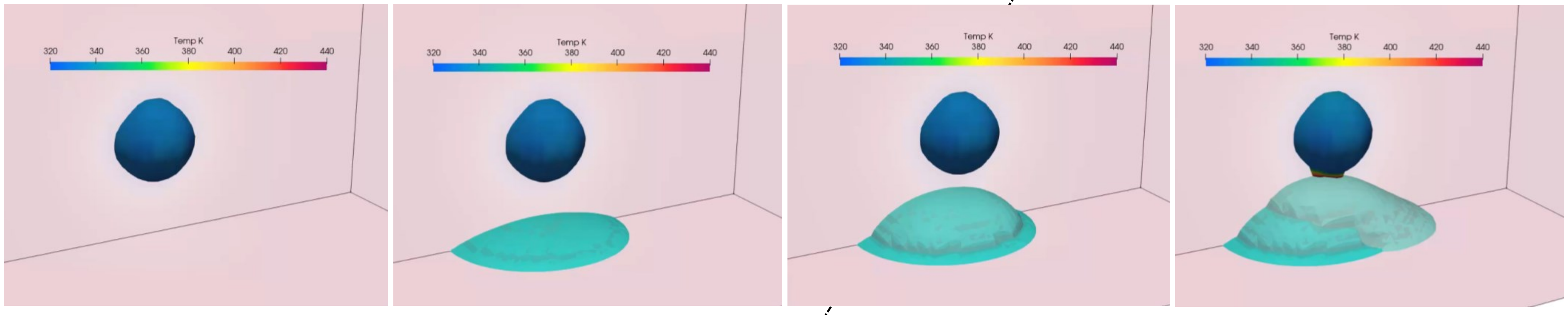
Assumption:
Negligible shrinkage during polymerization



simulation of a single droplet

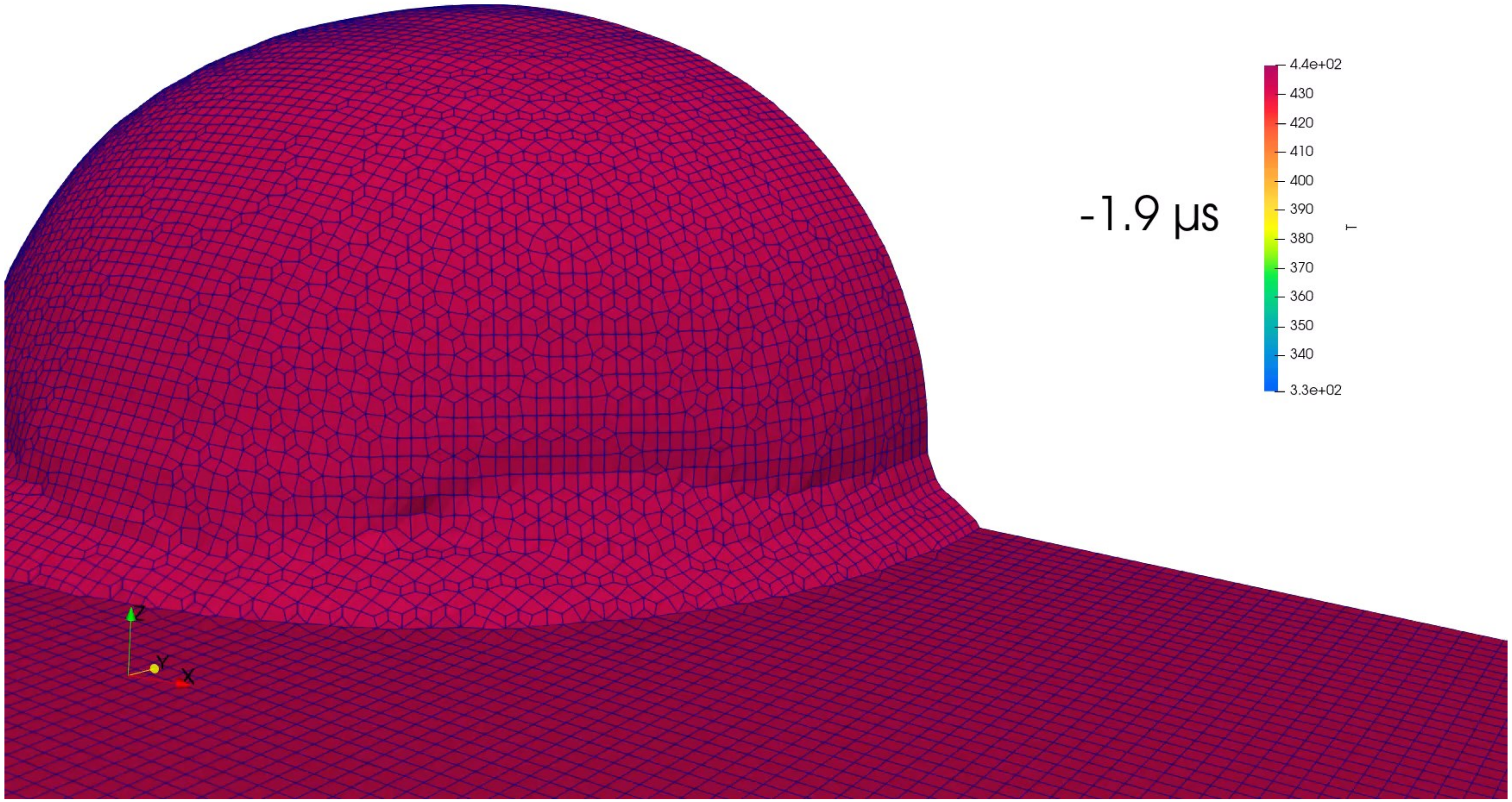
new simulation

- export STL → 0.5 α to contour → simulation
- import STL → *snappyHexMesh* → simulation



1st droplet *2nd droplet* *3rd droplet* *4th droplet*

Stacking of the droplets



exemplary simulation parameters

Parameter	Unit	Value
Setup		
droplet radius	m	9.85e-6
droplet speed	m/s	4
droplet temperature	K	328
Ink		
droplet mol weight	g/mol	240
droplet heat capacity	J/kg/K	1150
droplet density	kg/m³	1180
droplet dyn. viscosity	Pa.s	Polynom
droplet heat conductivity	W/m/K	0.219
droplet surface tension	N/m	0.045
Substrate		
wall friction	-	noSlip
contact angle	deg	constant
substrate temperature	K	433
substrate head capacity	W/m/K	0.219
heat transfert coefficient	W/m²/K	70
substrate thickness	m	100e-6

Method of the simulation studies

database → load data → simulation → evaluation (sigmoid fit) → save → analysis

```
parameter_ranges = {
    "x1": (0, 1e-6),
    "x2": (0, 2e-6),
    "x3": (0, 3e-6),

    "substrateTemp": (323, 433),
    "substrateThermalCond": (0.2, 400),
    "substrateThickness": (1e-6, 3000e-6),
    "contactAngle": (15, 39),
    "dropletRadius": (7e-6, 14e-6),
    "dropletVelocity": (4, 8),
    "dropletInitialTemp": (313, 343),
    "dropletThermalCond": (0.2, 0.6),
    "dropletSurfaceTension": (0.020, 0.070),
    "dropletViscosityLevel": (1, 3)
}
```

→ printing strategy → Full Factorial DoE

×

→ printing parameters → Latin Hypercube Sampling DoE

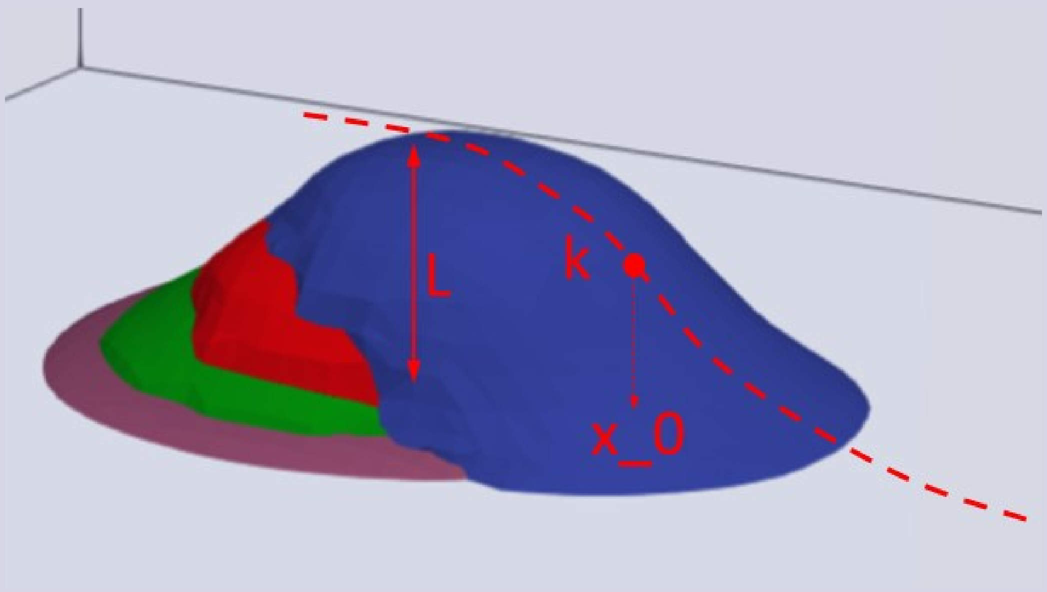
=

database

Points per Parameter k	*number of CFD Simulations k^13*
2	8 192
3	1 594 323
4	67 108 864
5	1 220 703 125

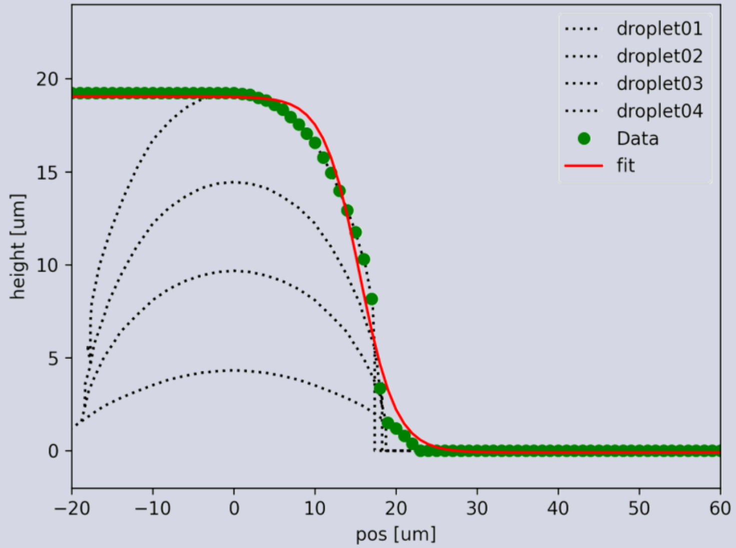
for comparison a Full-Factorial DoE of all parameters

Determining the droplet incline



stacking of 4 droplets

sigmoid-fit mapped to simulation



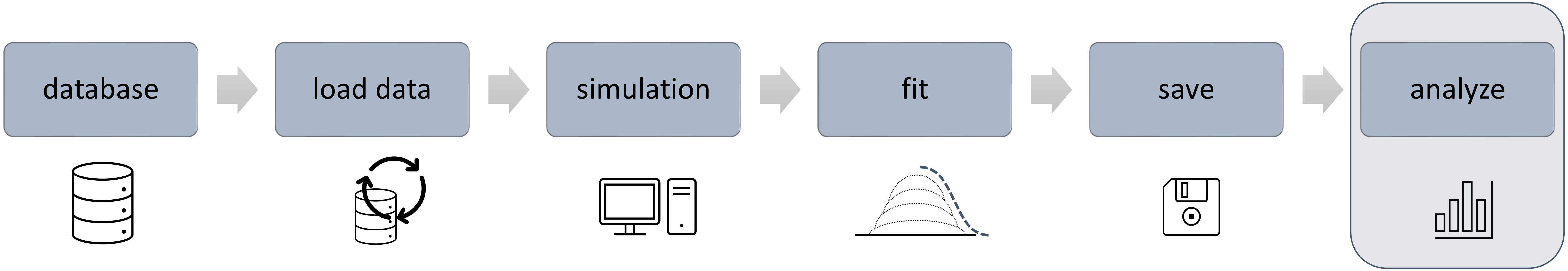
$$\tan(\alpha) = \frac{1}{4}\, k\, L$$

angle at steepest point (x_0)

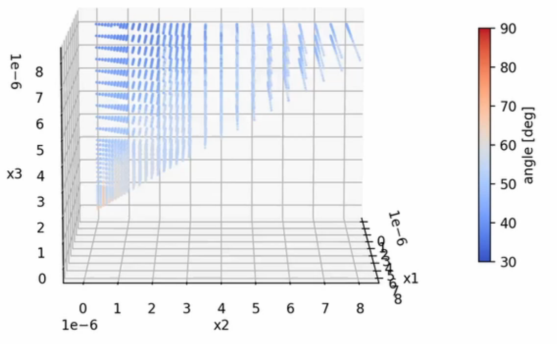
L	height
k	0.0 : flat ∞ : rectangular
x_0	x-position of the turning point

parameters of sigmoid-fit

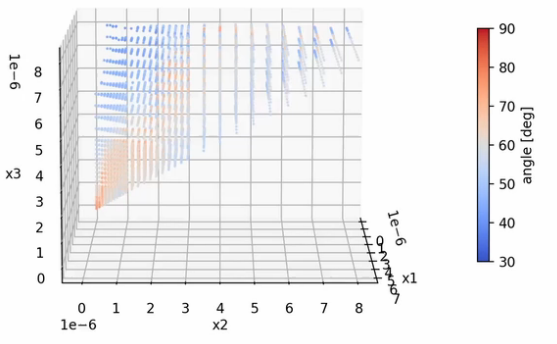
Analyzing the results



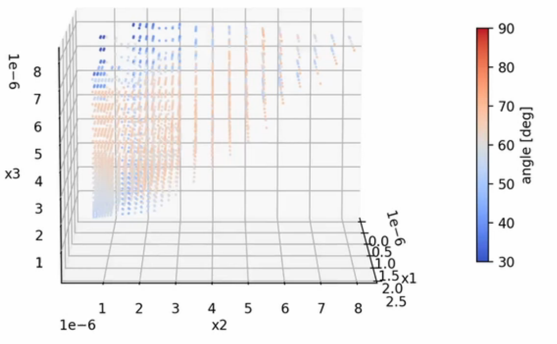
20 deg

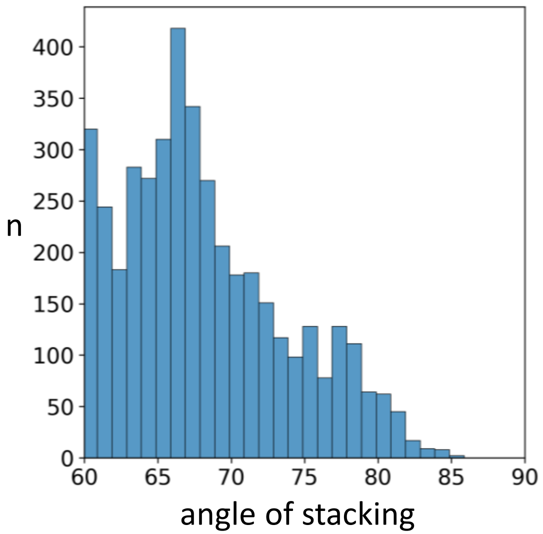


30 deg



40 deg



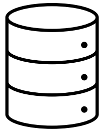
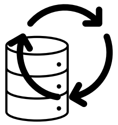
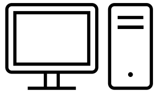
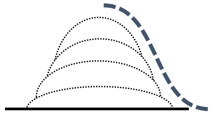
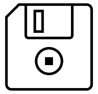


*visualization **4 out of 13** parameters*
*(these graphs contains 3 x 5500 x 4 = **66 k** CFD-simulations)*

stacking angles > 80 deg are possible !

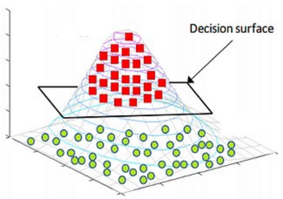
Current Activities: ML analysis and reduction of simulation time

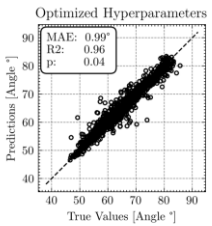
database → load data → simulation → fit → save → analyze

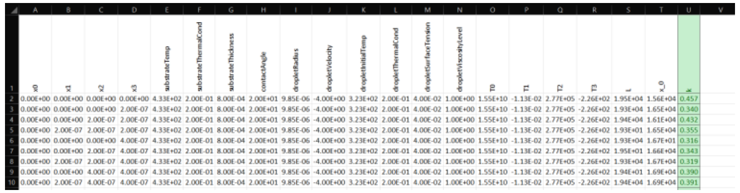







Machine Learning
to analyze data

Active Machine Learning
to reduce number of CFD-Simulations



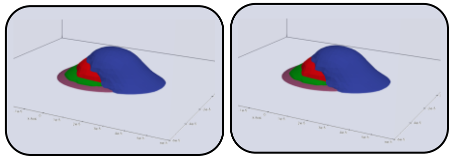




	x0	x1	x2	x3	substrateTemp	substrateThermalCond	substrateThickness	contactAngle	dropletRadius	dropletVelocity	dropletInitialTemp	dropletThermalCond	dropletSurfaceTension	dropletViscosityLevel	T0	T1	T2	T3	L	x_0	k
2	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.33E+02	2.00E-01	8.00E-04	2.00E+01	9.85E-06	-4.00E+00	3.23E+02	2.00E-01	4.00E-02	1.00E+00	1.55E+10	-1.13E-02	2.77E+05	-2.26E+02	1.95E+04	1.56E+04	0.457
3	0.00E+00	0.00E+00	0.00E+00	2.00E-07	4.33E+02	2.00E-01	8.00E-04	2.00E+01	9.85E-06	-4.00E+00	3.23E+02	2.00E-01	4.00E-02	1.00E+00	1.55E+10	-1.13E-02	2.77E+05	-2.26E+02	1.93E+04	1.65E+04	0.340
4	0.00E+00	0.00E+00	2.00E-07	2.00E-07	4.33E+02	2.00E-01	8.00E-04	2.00E+01	9.85E-06	-4.00E+00	3.23E+02	2.00E-01	4.00E-02	1.00E+00	1.55E+10	-1.13E-02	2.77E+05	-2.26E+02	1.94E+04	1.61E+04	0.432
5	0.00E+00	2.00E-07	2.00E-07	2.00E-07	4.33E+02	2.00E-01	8.00E-04	2.00E+01	9.85E-06	-4.00E+00	3.23E+02	2.00E-01	4.00E-02	1.00E+00	1.55E+10	-1.13E-02	2.77E+05	-2.26E+02	1.93E+04	1.65E+04	0.355
6	0.00E+00	0.00E+00	0.00E+00	4.00E-07	4.33E+02	2.00E-01	8.00E-04	2.00E+01	9.85E-06	-4.00E+00	3.23E+02	2.00E-01	4.00E-02	1.00E+00	1.55E+10	-1.13E-02	2.77E+05	-2.26E+02	1.93E+04	1.67E+04	0.316
7	0.00E+00	0.00E+00	2.00E-07	4.00E-07	4.33E+02	2.00E-01	8.00E-04	2.00E+01	9.85E-06	-4.00E+00	3.23E+02	2.00E-01	4.00E-02	1.00E+00	1.55E+10	-1.13E-02	2.77E+05	-2.26E+02	1.95E+04	1.66E+04	0.343
8	0.00E+00	2.00E-07	2.00E-07	4.00E-07	4.33E+02	2.00E-01	8.00E-04	2.00E+01	9.85E-06	-4.00E+00	3.23E+02	2.00E-01	4.00E-02	1.00E+00	1.55E+10	-1.13E-02	2.77E+05	-2.26E+02	1.93E+04	1.67E+04	0.319
9	0.00E+00	0.00E+00	4.00E-07	4.00E-07	4.33E+02	2.00E-01	8.00E-04	2.00E+01	9.85E-06	-4.00E+00	3.23E+02	2.00E-01	4.00E-02	1.00E+00	1.55E+10	-1.13E-02	2.77E+05	-2.26E+02	1.94E+04	1.69E+04	0.390
10	0.00E+00	2.00E-07	4.00E-07	4.00E-07	4.33E+02	2.00E-01	8.00E-04	2.00E+01	9.85E-06	-4.00E+00	3.23E+02	2.00E-01	4.00E-02	1.00E+00	1.55E+10	-1.13E-02	2.77E+05	-2.26E+02	1.94E+04	1.69E+04	0.391

new parameters

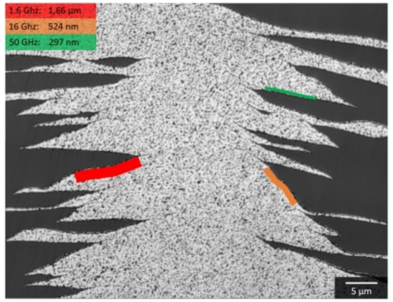
Machine Learning Model

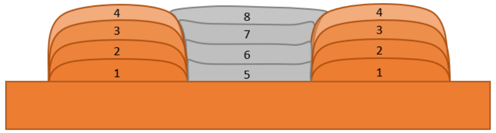


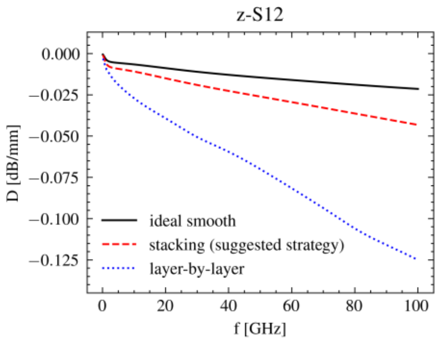
results

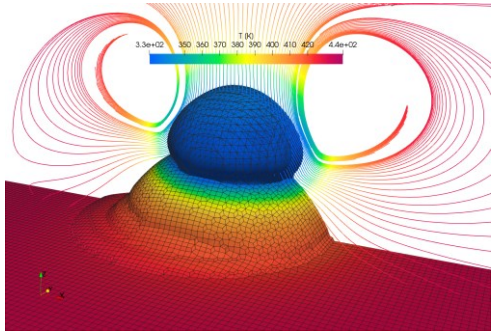
Recap

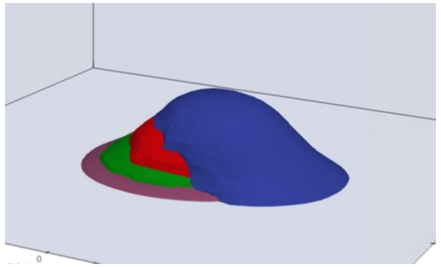
Thank you!

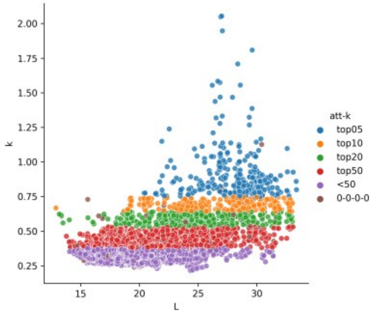












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