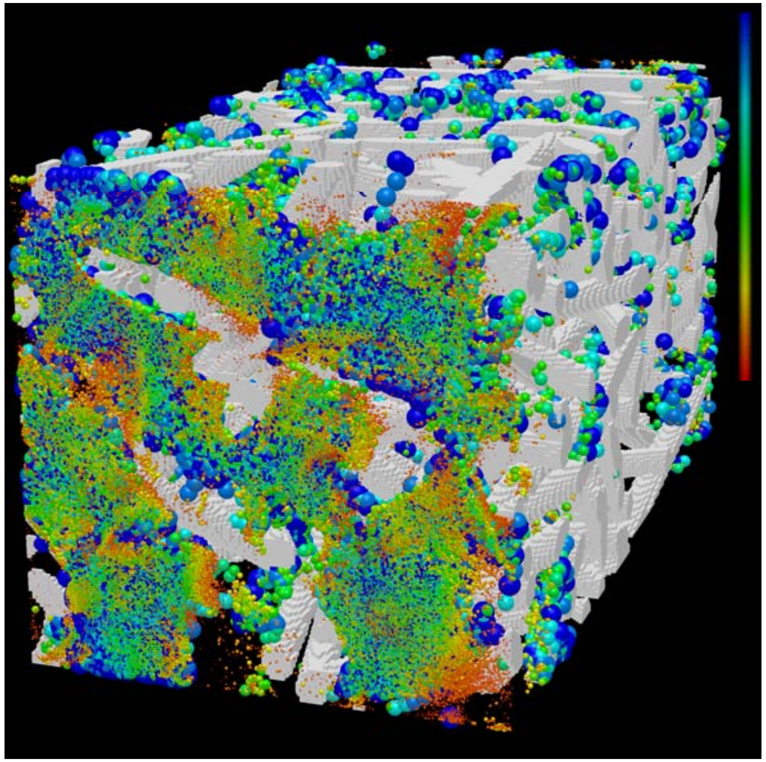
Filtration efficiency and filter life time of nonwovens



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Fraunhofer ITWM
Abteilung Strömung und komplexe Strukturen
Dept. Flows and Complex Structures

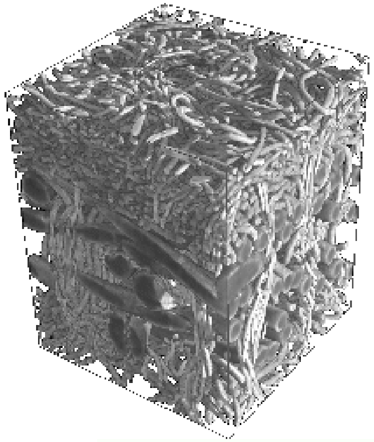
Fraunhofer Chalmers Research Centre Industrial Mathematics

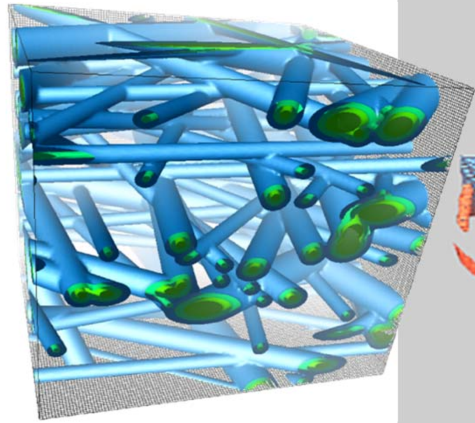
March 9, 2005.

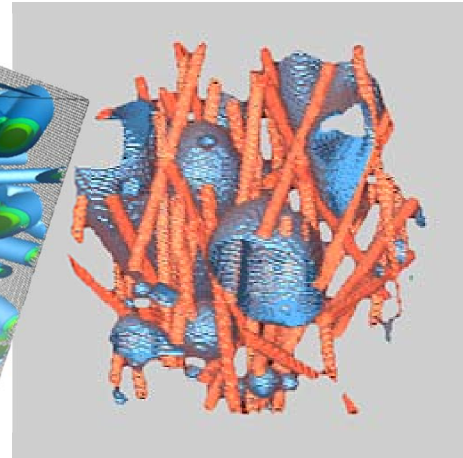
Fraunhofer Institut Techno- und Wirtschaftsmathematik

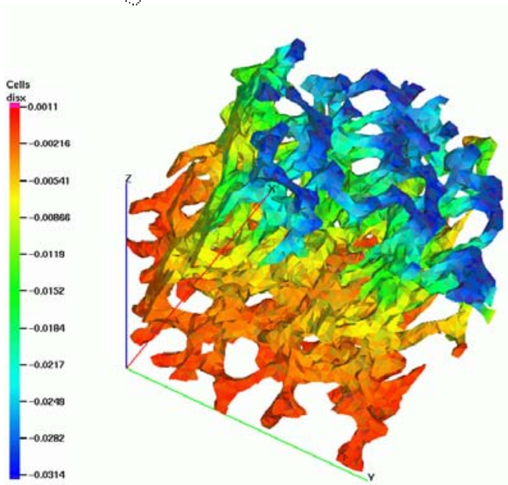
Micro structure simulation and virtual material design

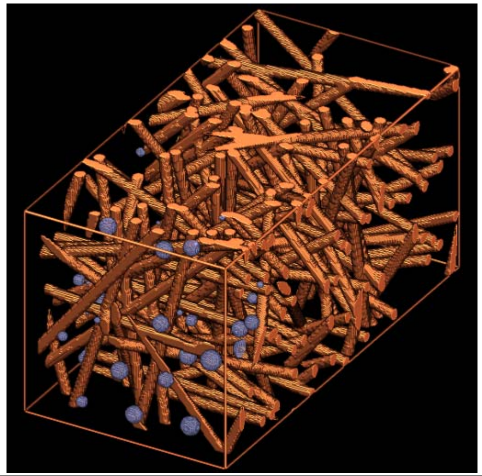
- Virtual 3D material models
- Structure generator + simulator GeoDict (www.geodict.com)
- Computation of material parameters
  - flow resistivity
  - permeability, capillary pressure
  - acoustic absorption
  - effective elasticity tensor
- Sequences of simulations to optimize material geometry
- FilterDict: particle filtration











GEO DICT

FILTER DICT

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Multi scale problem: Idea of virtual material design

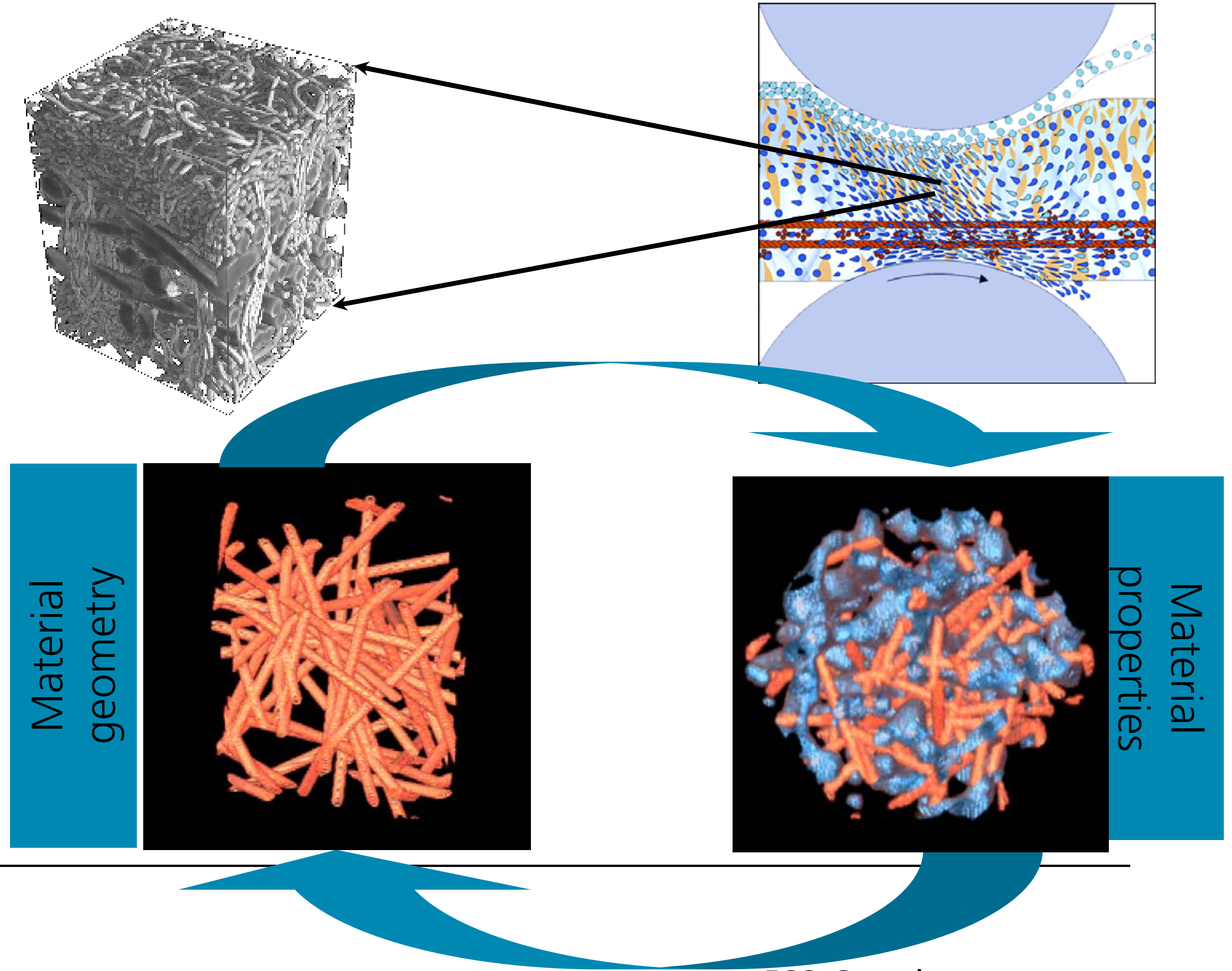
Influence material properties through microscopic geometry

→ Solve partial differential equation on the micro scale

Micro-Macro-Coupling:

- Homogenization
- Upscaling
- Averaging

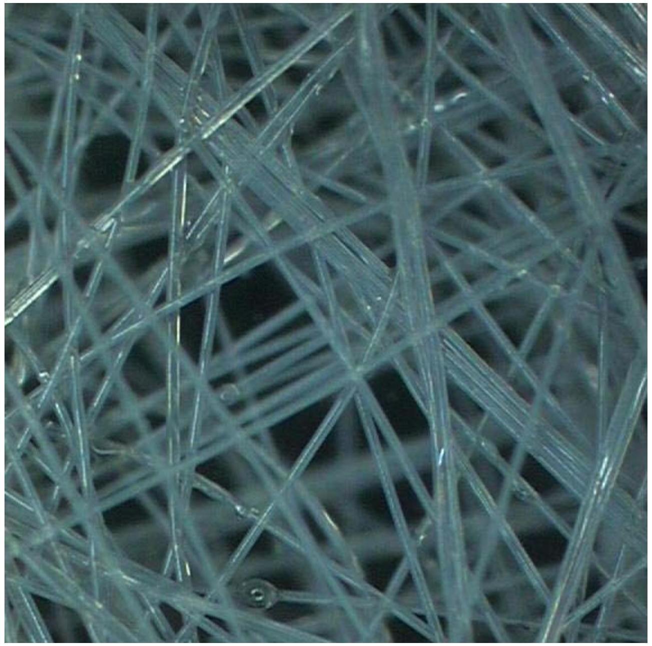
Micro structure simulation + averaging = effective material property



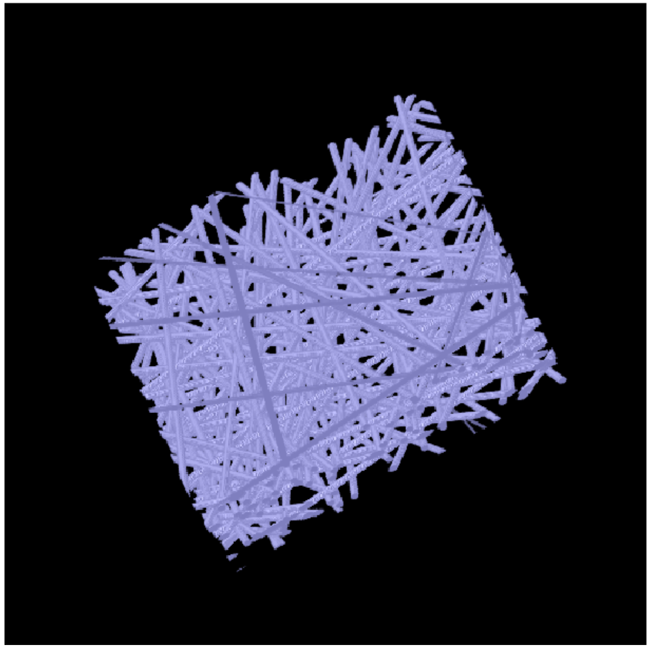
Virtual Filter Material Design with GeoDict & FilterDict

- The micro geometry of a filter media has a decisive influence on ist filtration properties
- Simulations must work on fully 3d complex geometries
- Create mathematical geometry models rather than use ONLY images of micro structure
- Design (optimize) by varying a few „average properties“
- Combine solvers for fluid flow, particle tracking, electrostatic charges, etc.
- Couple micro to macro, e.g. as local permeability in filter housing simulation
- GeoDict is commercial software based on work that won the 2001 Fraunhofer Prize
- FilterDict is commercial software based on in-house parallel code
- Have parallelized codes available for current in-house use, future desk top users

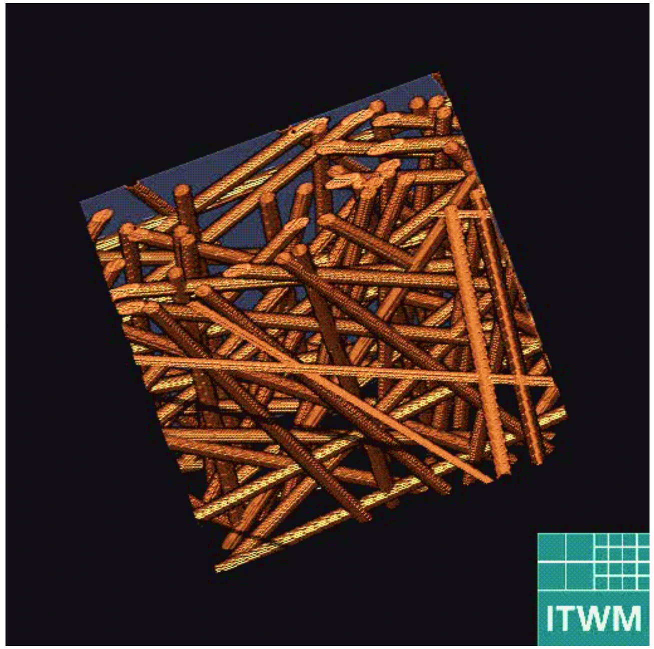
The geometric nonwoven model



Microscopy



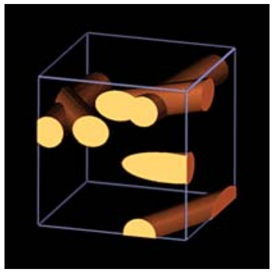
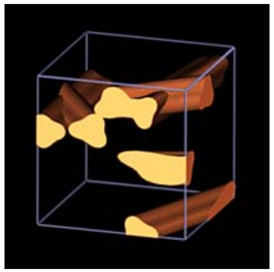
Fiber modell



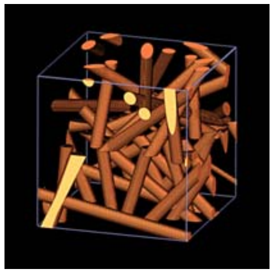
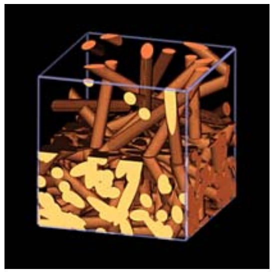
Flow simulation in the model

Possible variations: e.g.

- Cross sections

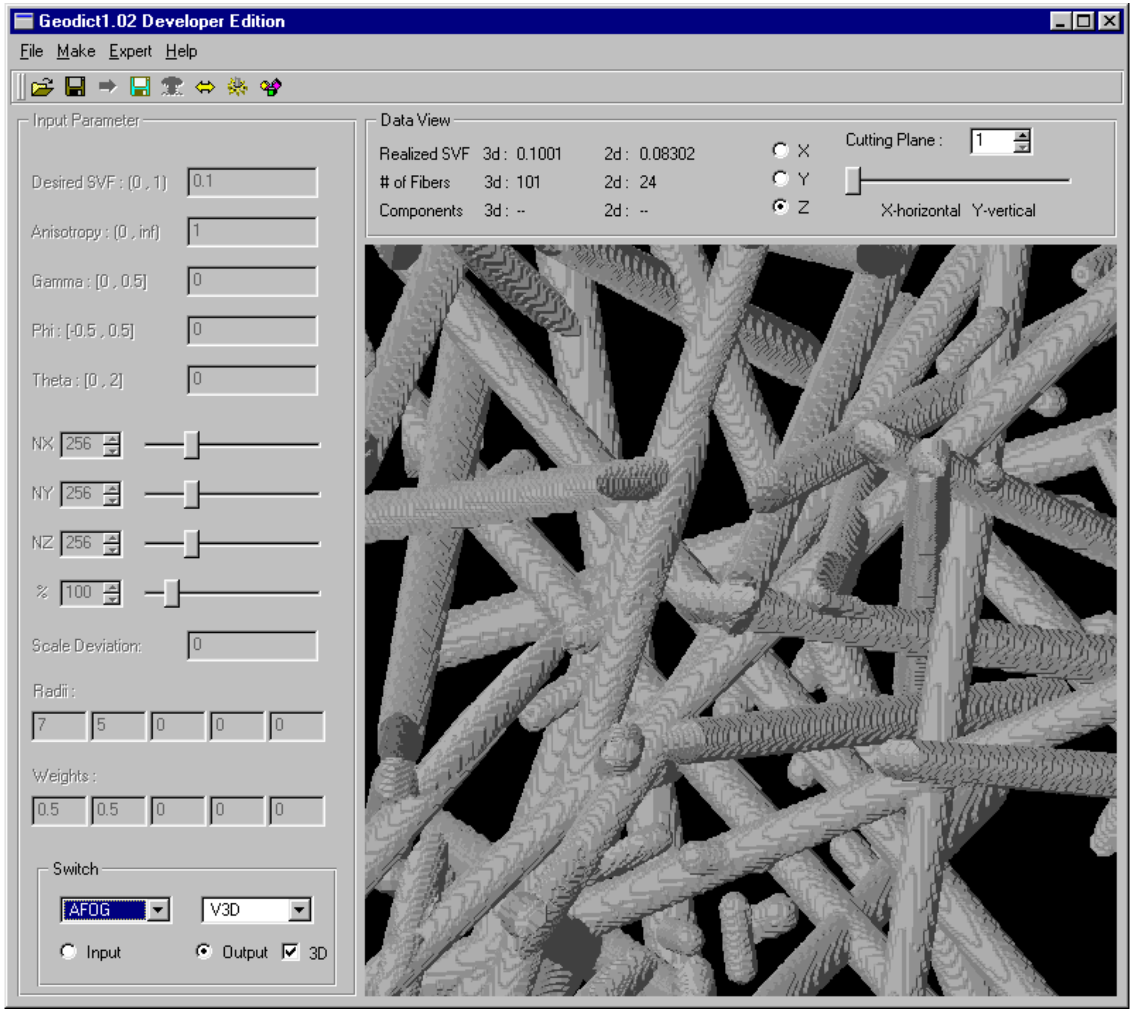



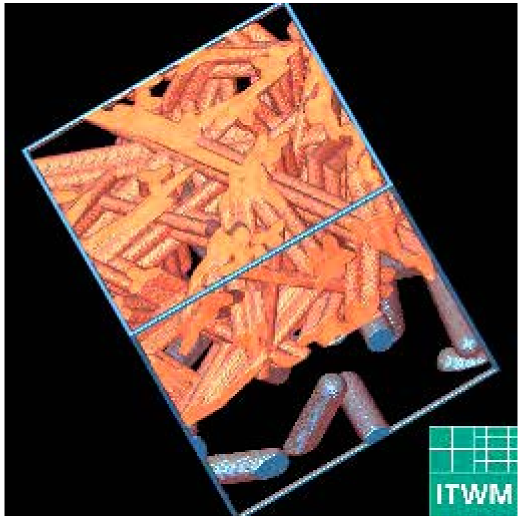
- Layers

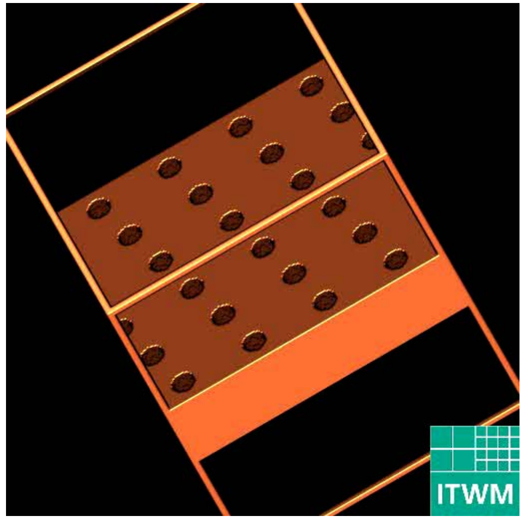



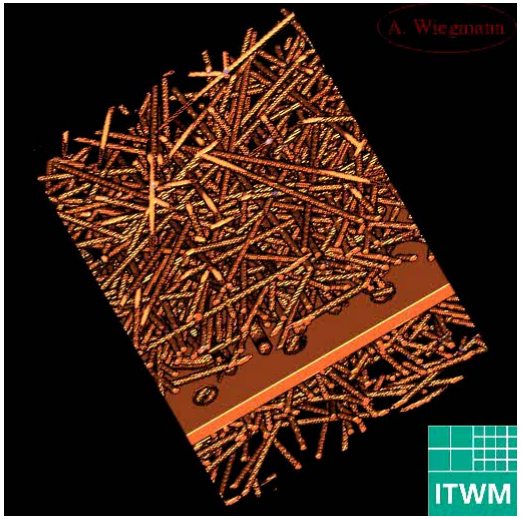
- Anisotropy

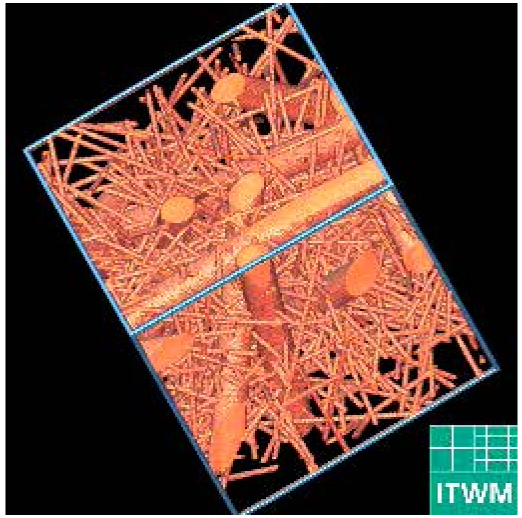

GeoDict: 3d structure generation











GeoDict
FilterDict

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FCC, Gotenburg

09 March 2005

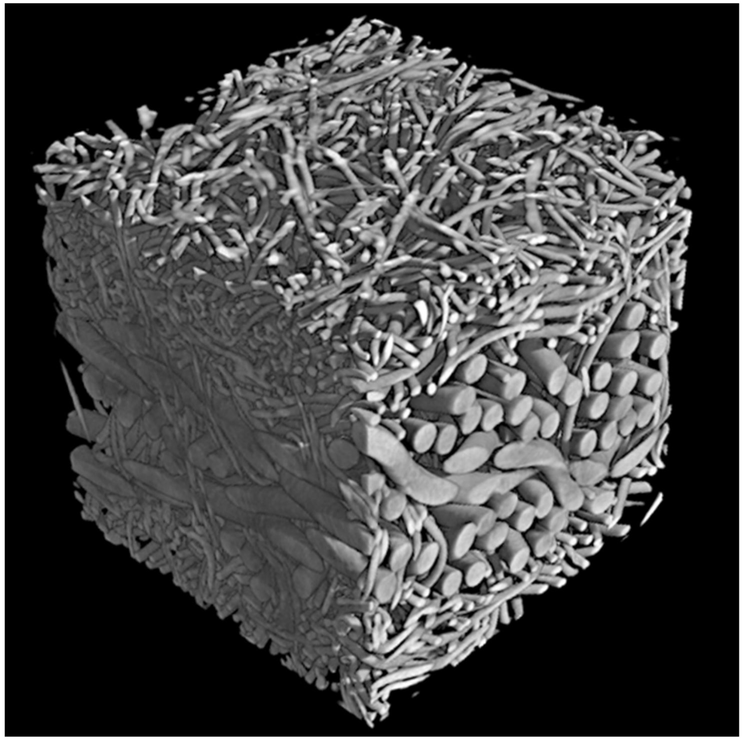
Transverse isotrope fiber orentation probability and nonwoven material density

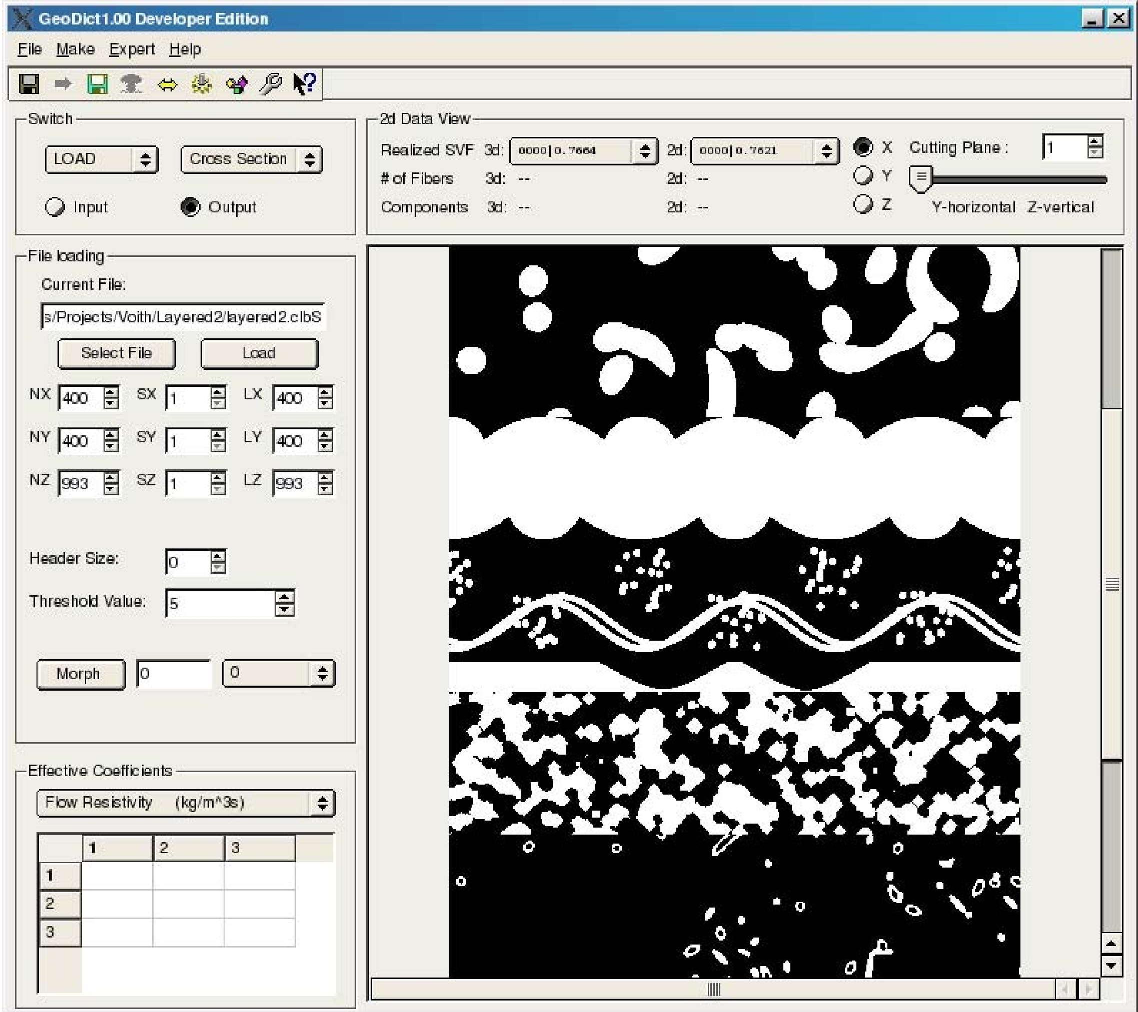
$$p(\vartheta,\varphi)=\frac{1}{4\pi}\frac{\beta\sin\vartheta}{(1+(\beta^2-1)\cos^2\vartheta)^{3/2}} \quad , \qquad \vartheta\in[0,\pi),\varphi\in[0,2\pi)$$

Density of a Poisson line process
with random fiber diameter r
and E(r²) its second moment.

$$\lambda=-\log\frac{V_V}{\rho\mathrm{E}(r^2)}$$

Filtration properties can be computed for real and simulated data





Synchrotron image vs. generated structure (paper dewatering felt)

GEO DICT

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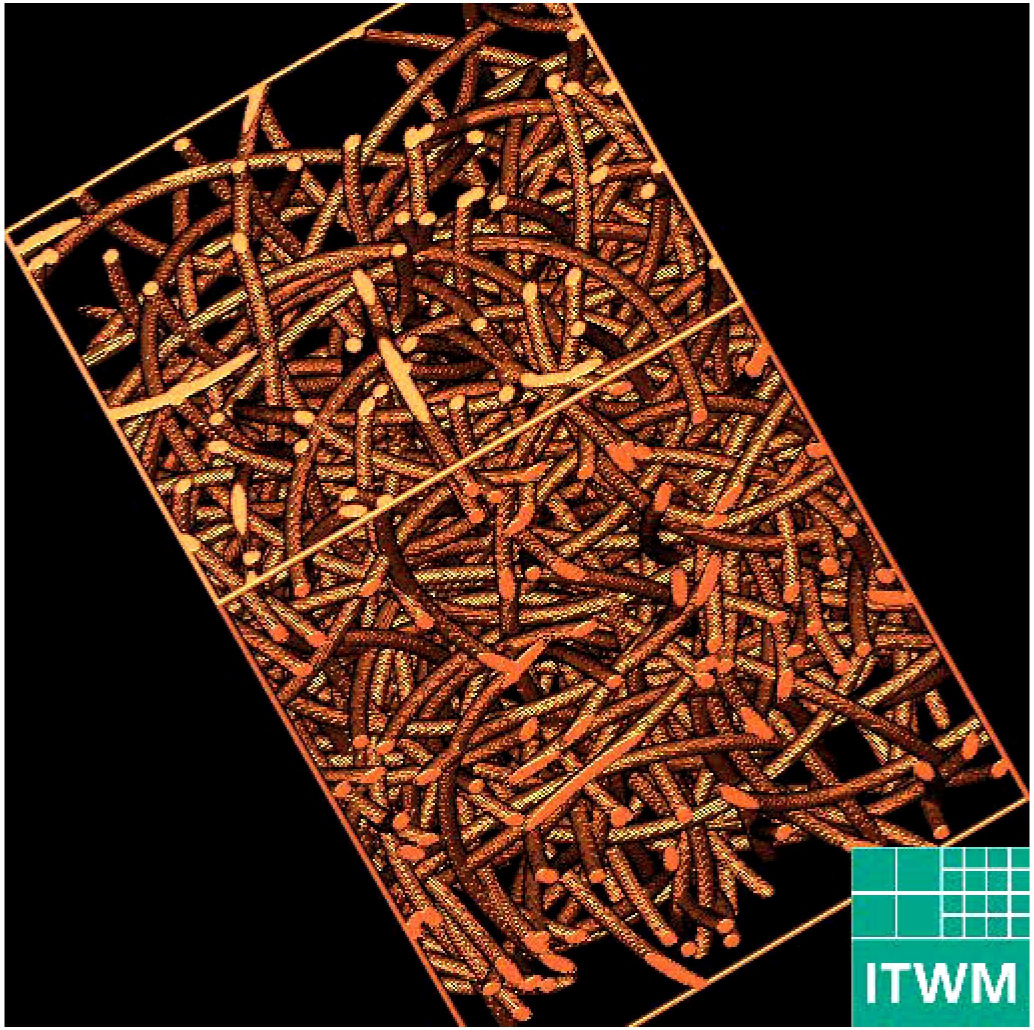
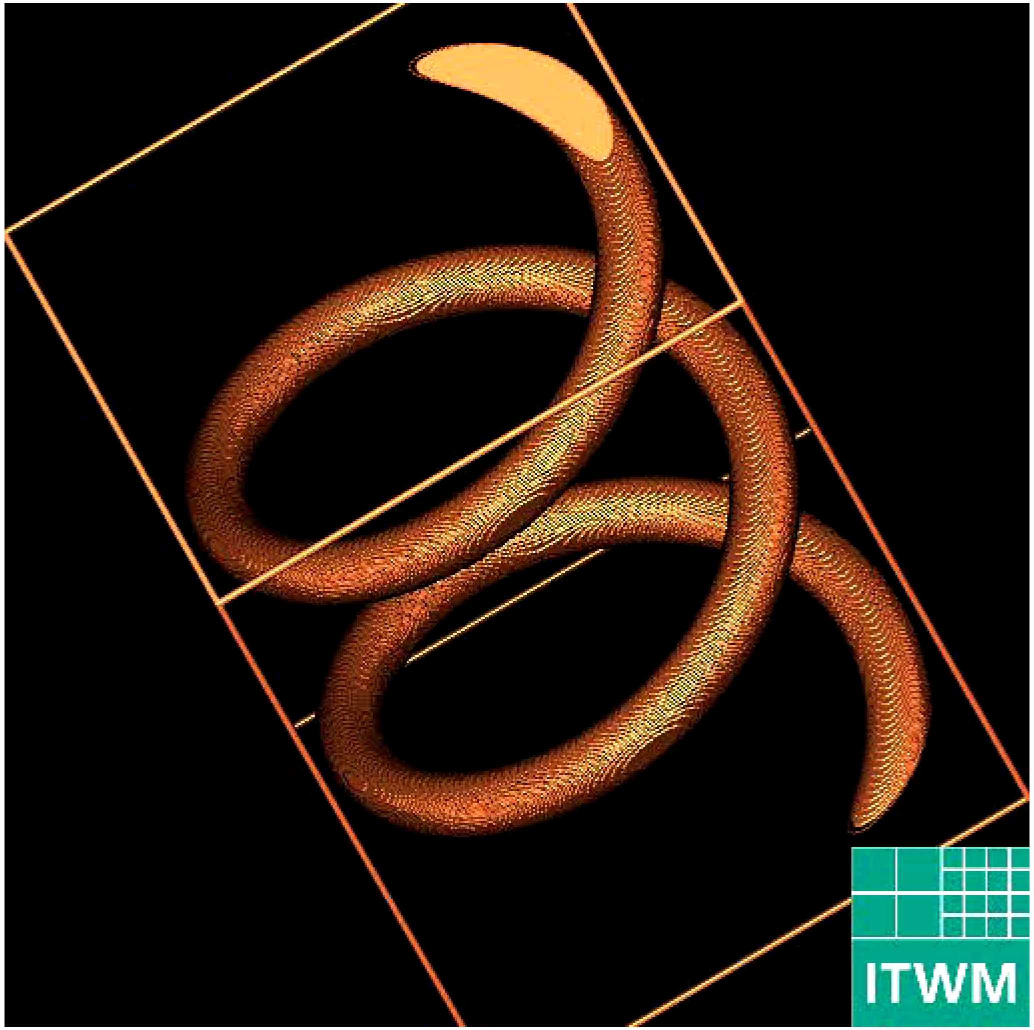
Crimped fibers





Eulerian description of stationary Stokes flow and effective permeability of a porous medium

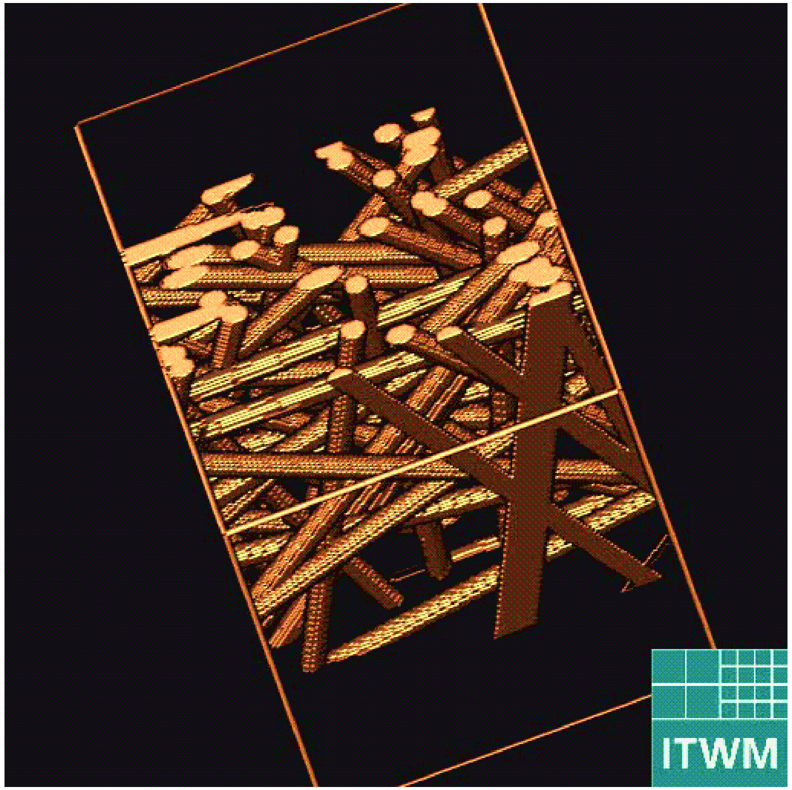
$\mu\,\Delta\vec{u} + \vec{f} = \nabla p$: momentum balance

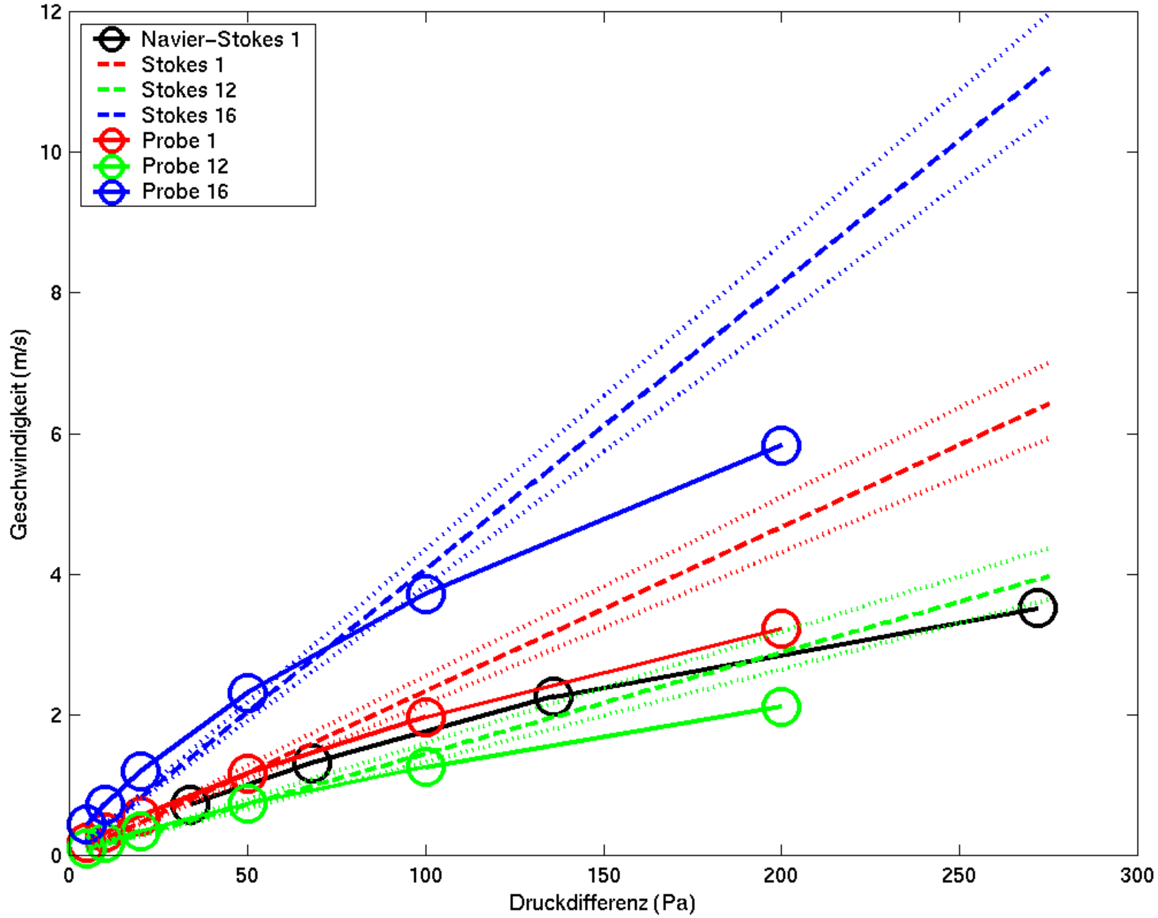
$div\,\vec{u} = 0$: incompressible conservation of mass

$\vec{u} = 0 \text{ on } \Gamma$: No-slip on fiber surfaces

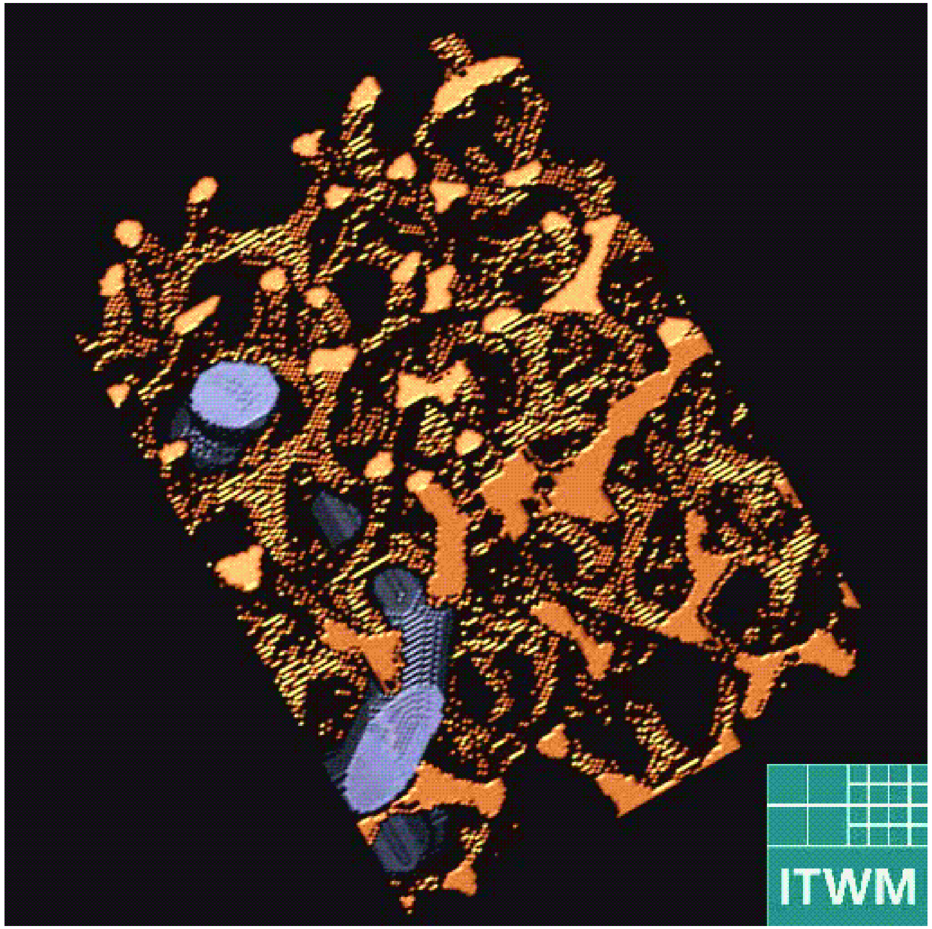
$$\kappa^{*}_{ij} = \frac{\iiint\limits_{V} \chi_{V_f}\; u(e_i)\, e_j \, dxdydz}{\iiint\limits_{V} 1 \, dxdydz}$$

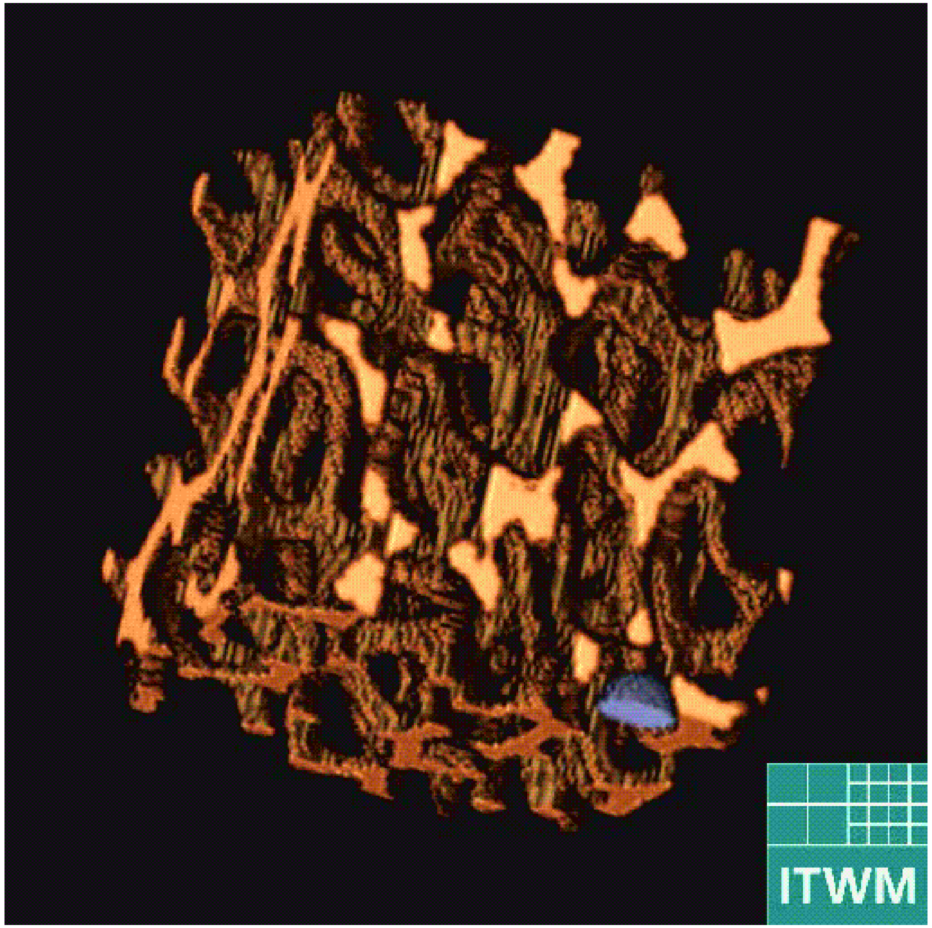
Flow Solver Validation: Navier-Stokes





Purely geometric properties: path of the largest penetrating particle





Filter efficiency simulation setup

- Follow closely the „standard“ testing procedure
- Media generated stochastically or from tomography, e.g. 2-4 layers of nonwoven
- Flow field solves (Navier-) Stokes equations, e.g. air at 20°C and 16 cm/sec.
- Spherical particles have given probability per size, e.g. Arizona dust between 300nm – 16µm diameter.
- Electric field is computed from surface charges on fibers, typically unknown magnitude and distribution.
- Stochastic differential equation for particle motion in the flow
- Particle – fiber and particle – deposited particle interaction

Mechanisms of Filtration

Knowing the flow field and the particle fiber interaction, the filter efficiency can be predicted.

Particle impact by:

A: direct interception

B: inertial impaction

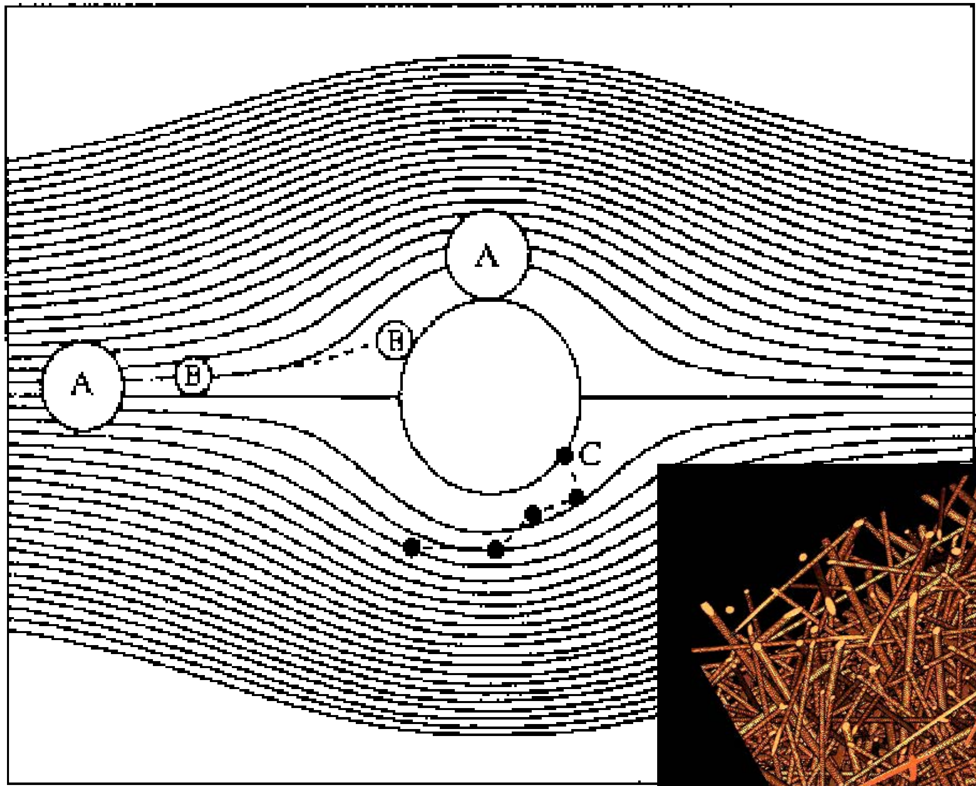
C: diffusional deposition

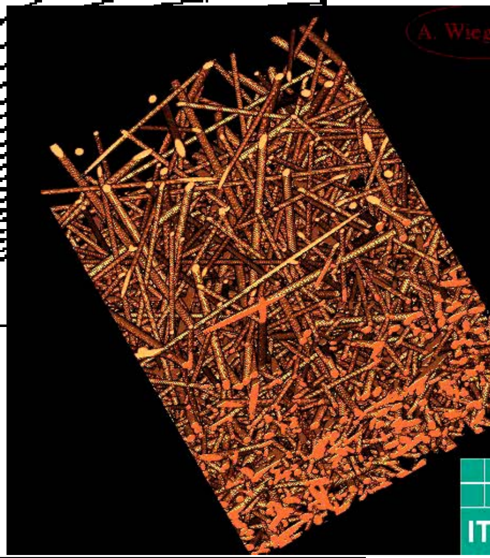
D: other effects (gravity,...)

E: multiple fiber interception

F: clogging

G: electric field



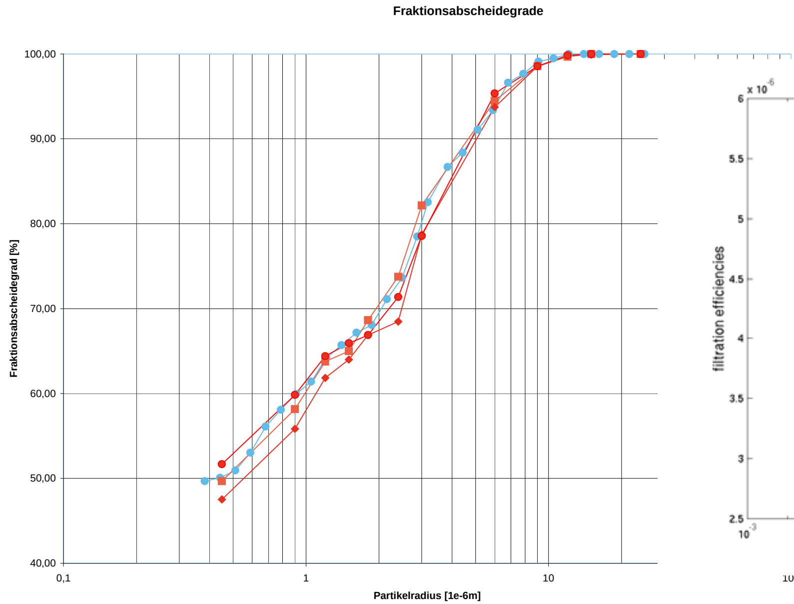


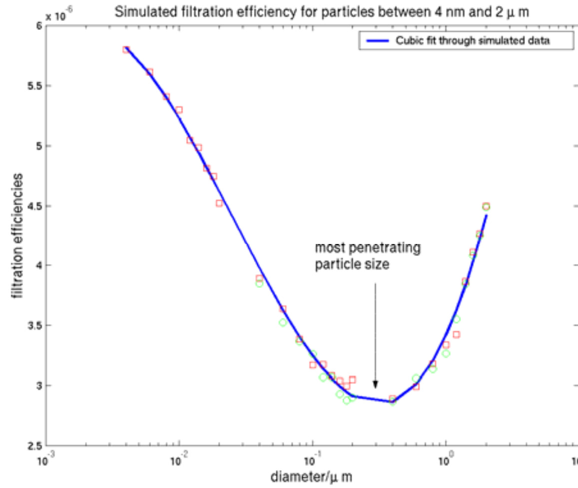
Particle – Fiber Collisions (Boundary Conditions)

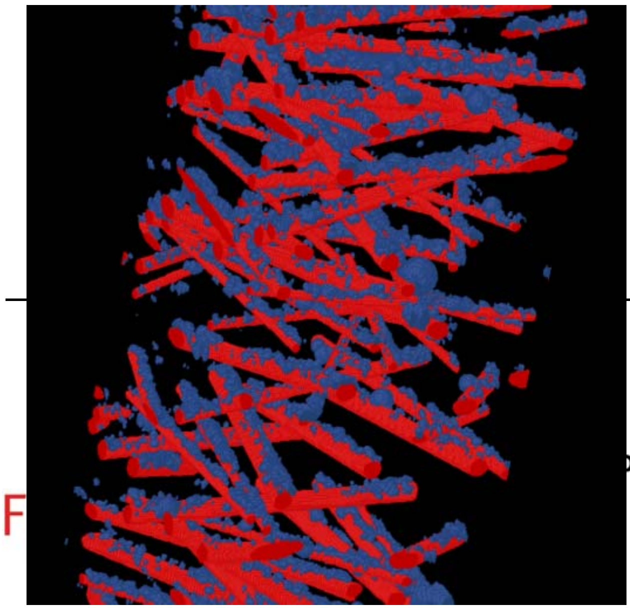
- Particles loose momentum and energy at collision
- Particles can bounce or break off if adhesion force is overcome
- Many fiber interactions are taken into account (sieving)
- Filtration by previously caught particles
- Soot models
- … (other effects could be modelled)

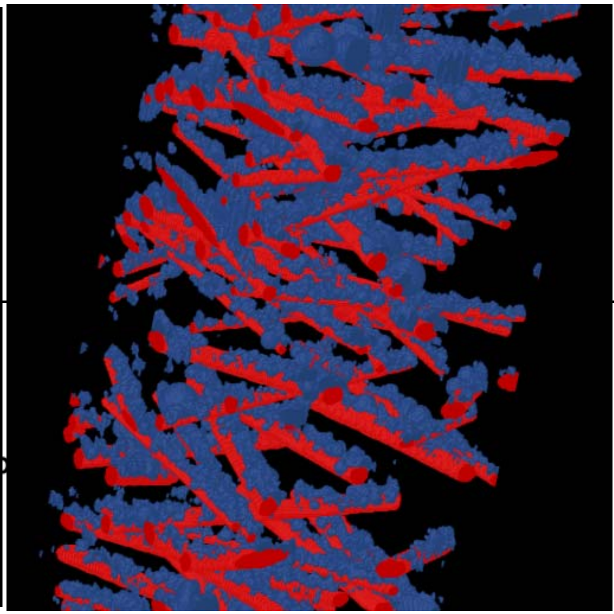
Results of the filtration simulation

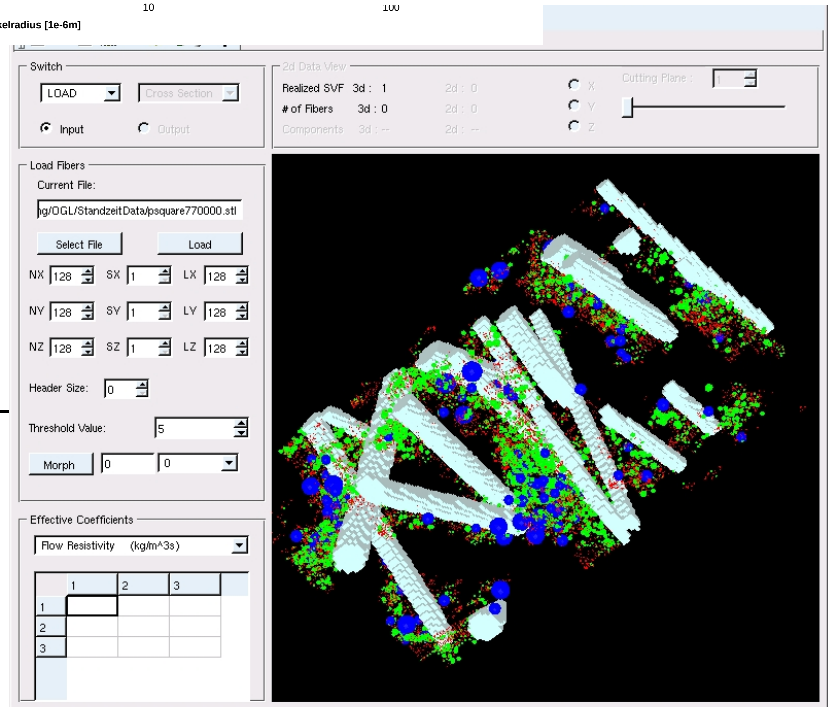
- Filter efficiency
- Most penetrating particle size
- Dirt distribution
- Clogging
- Local pressure drop
- Adhesion and dislocation of dirt
- Effects of electrostatic charges

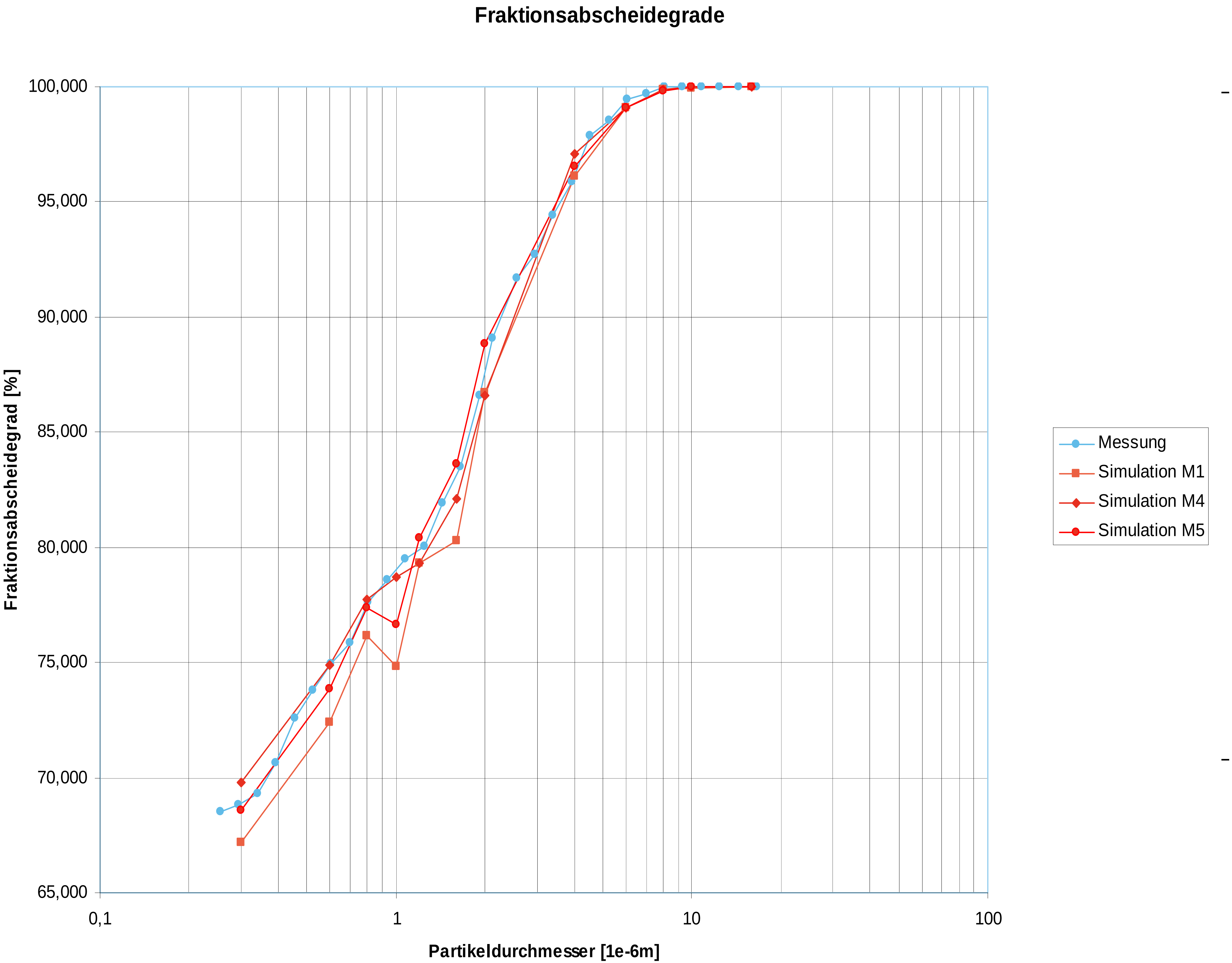






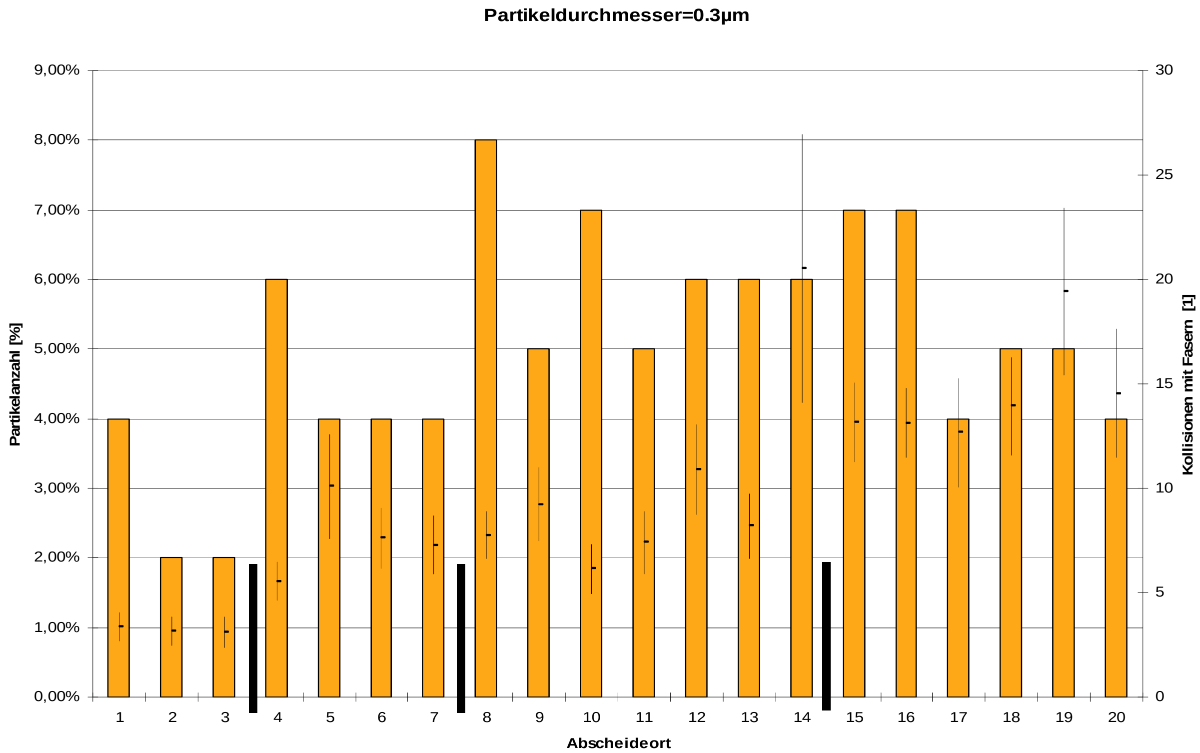


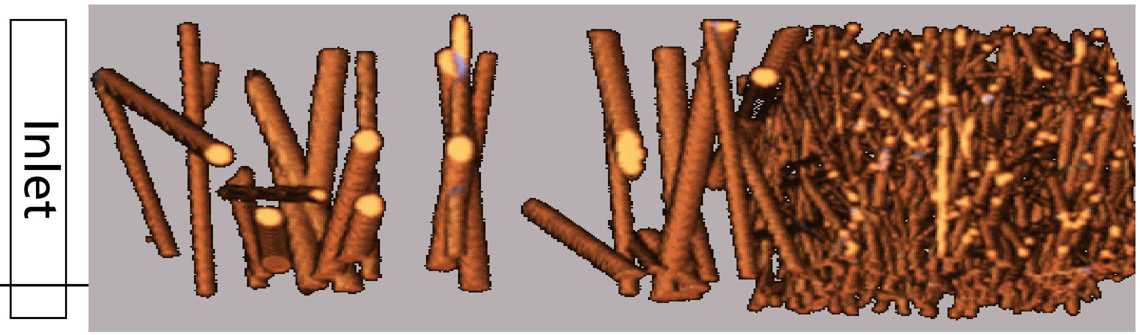


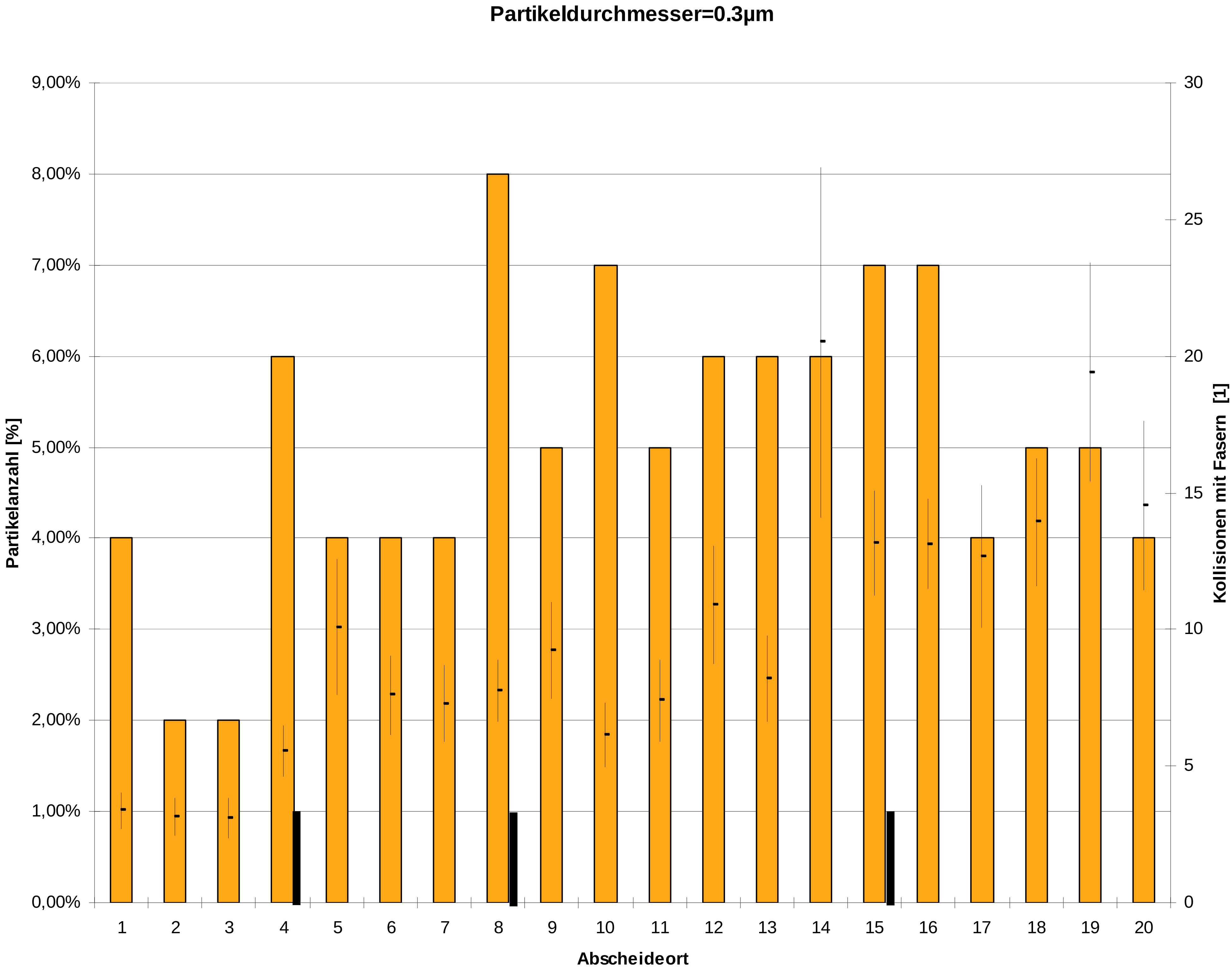

Fraktionsabscheidegrade
100,000
95,000
90,000
85,000
80,000
75,000
70,000
65,000
Fraktionsabscheidegrad [%]
0,1
1
10
100
Partikeldurchmesser [1e-6m]
Messung
Simulation M1
Simulation M4
Simulation M5

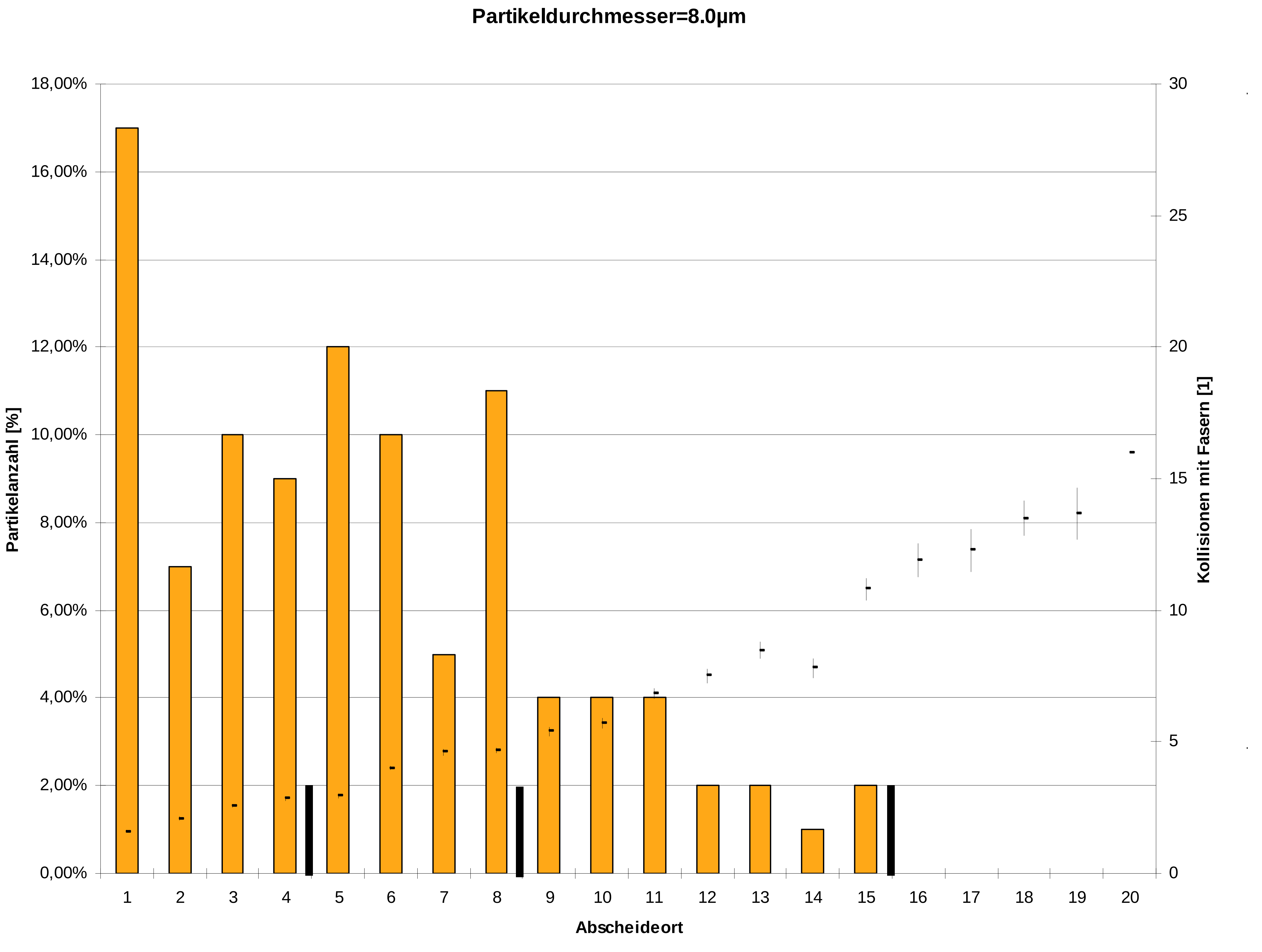
Deposition diagram

- Deposition locations are 64 64µm layers.
- Orange: particle numbers
- Lines: mean value and standard deviation of number of collisions
- Example: Layer 15 contains 7% of the filtered particles. Those had on average 13.15 collisions with standard deviation 1.9
- 4 layers on gradient material indicated by thick black lines:

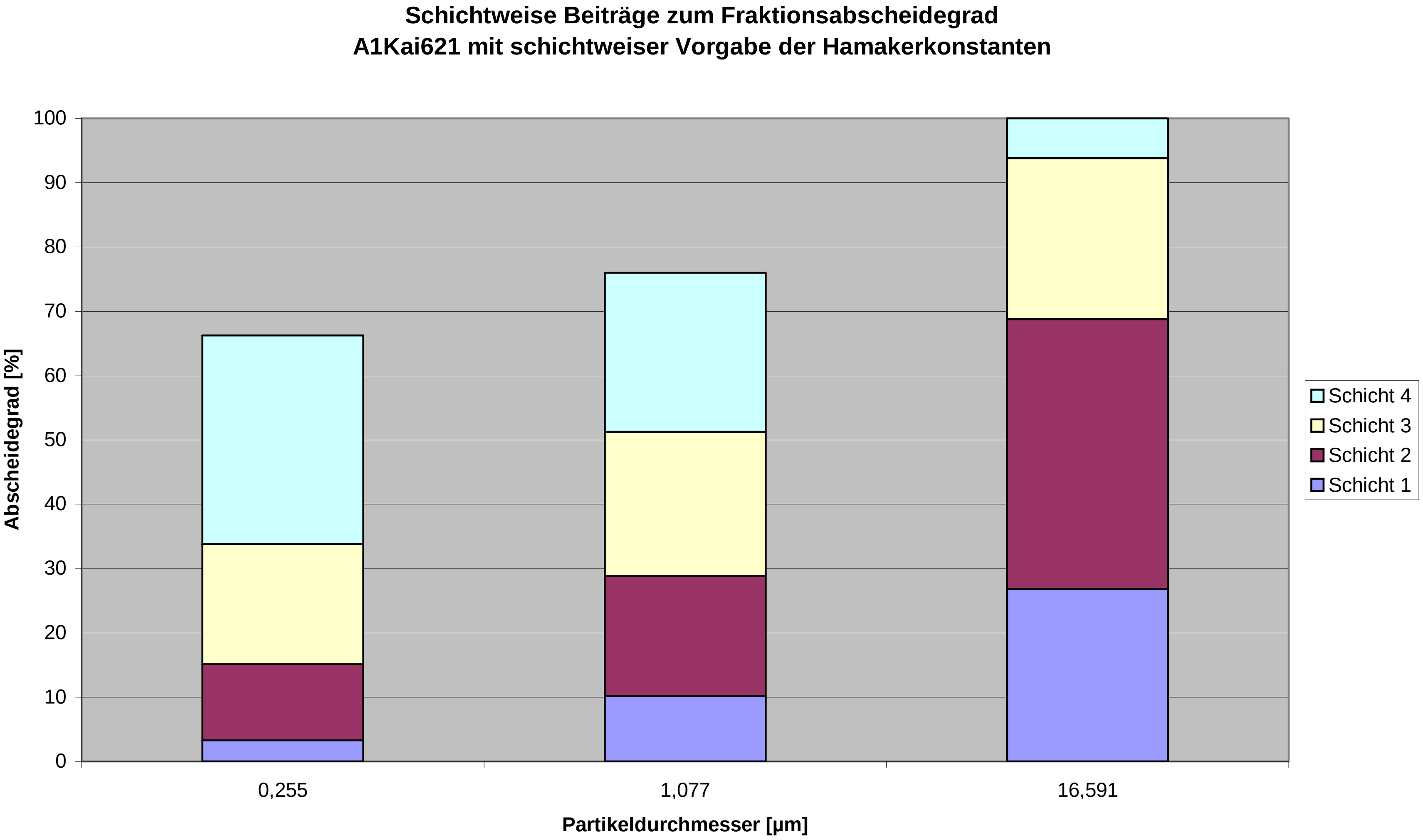




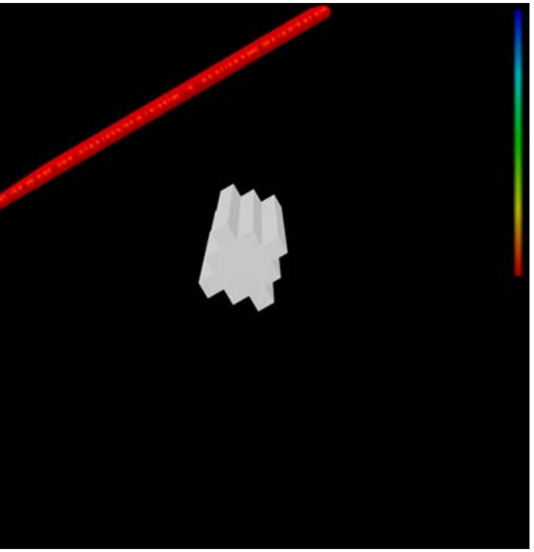
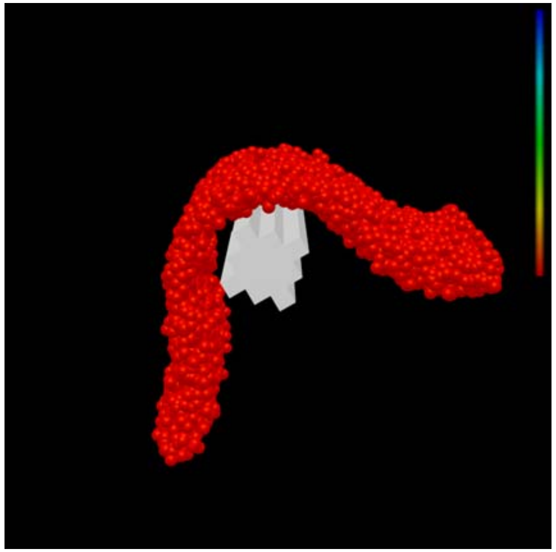
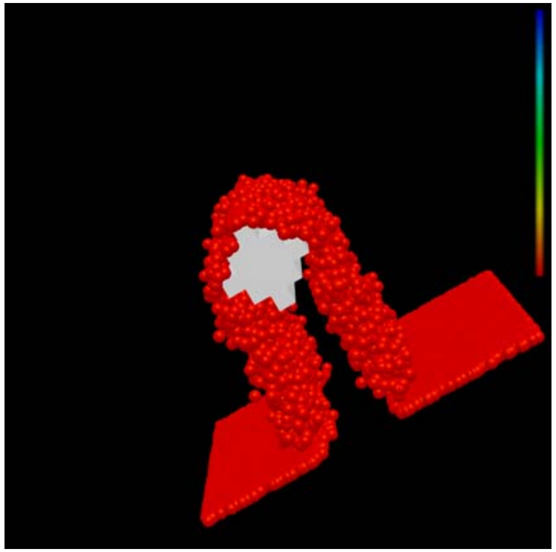
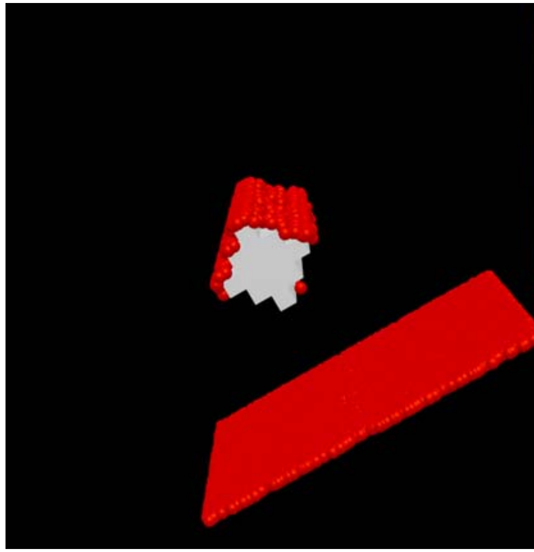
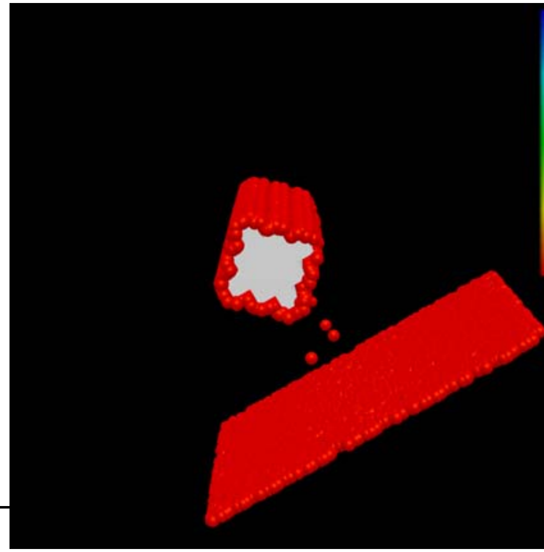

Partikeldurchmesser=0.3µm
Partikelanzahl [%]
9,00%
8,00%
7,00%
6,00%
5,00%
4,00%
3,00%
2,00%
1,00%
0,00%
Kollisionen mit Fasern [1]
30
25
20
15
10
5
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Abscheideort


Partikeldurchmesser=8.0µm
18,00%
16,00%
14,00%
12,00%
10,00%
8,00%
6,00%
4,00%
2,00%
0,00%
Partikelanzahl [%]
30
25
20
15
10
5
0
Kollisionen mit Fasern [1]
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
Abscheideort

Deposition of different size particles in the different layers



Influence of electrostatic surface charges

Depositon of uniform size particles on a single fiber in the absence and in the presence of an electric field:

- **deposition rate doubles,**
- **particles also stick to the „back“ of the fiber.**

Filter life time simulation setup

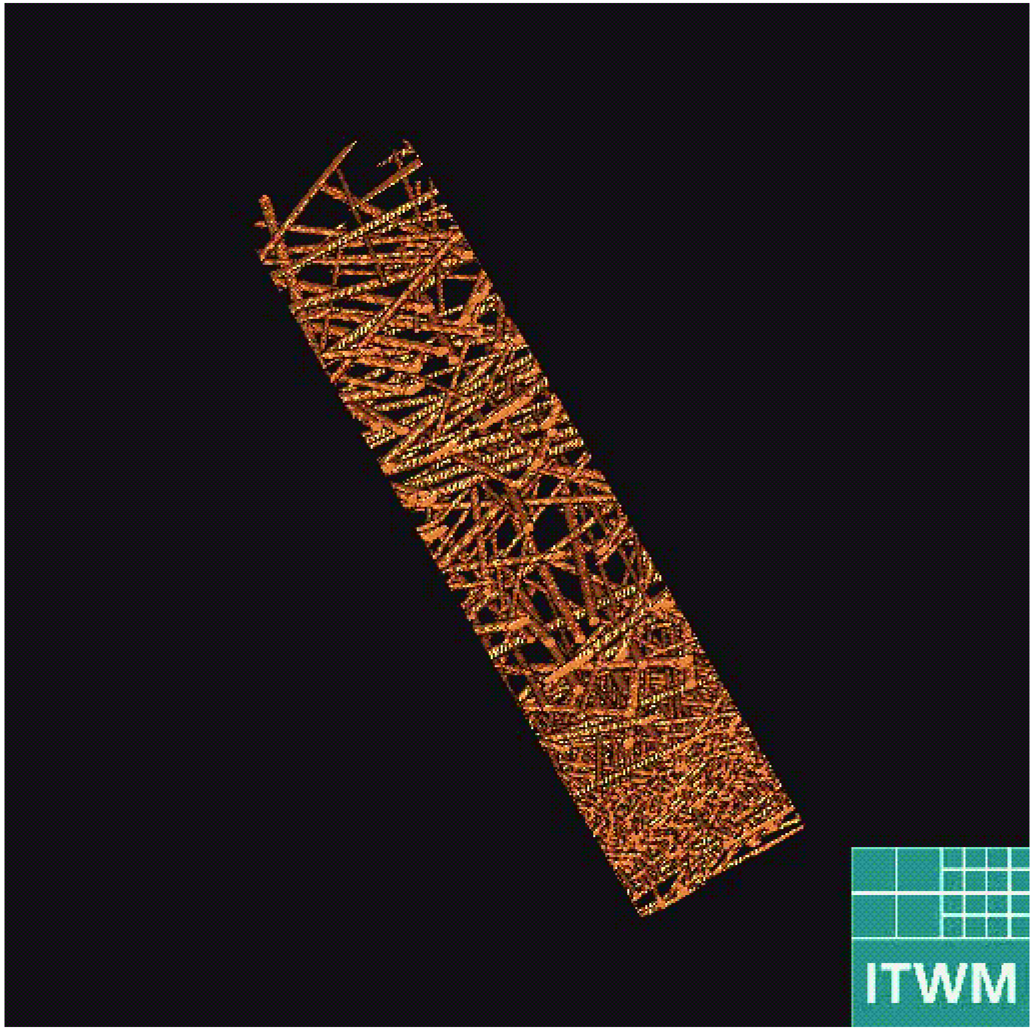
- Follow closely the „standard“ testing procedure
- Run filter efficiency computation with dirt model for some amount of dirt.
- Deposit the dirt: „enlarge“ fibers
- Recompute flow field and pressure drop, efficient through use of previous flow

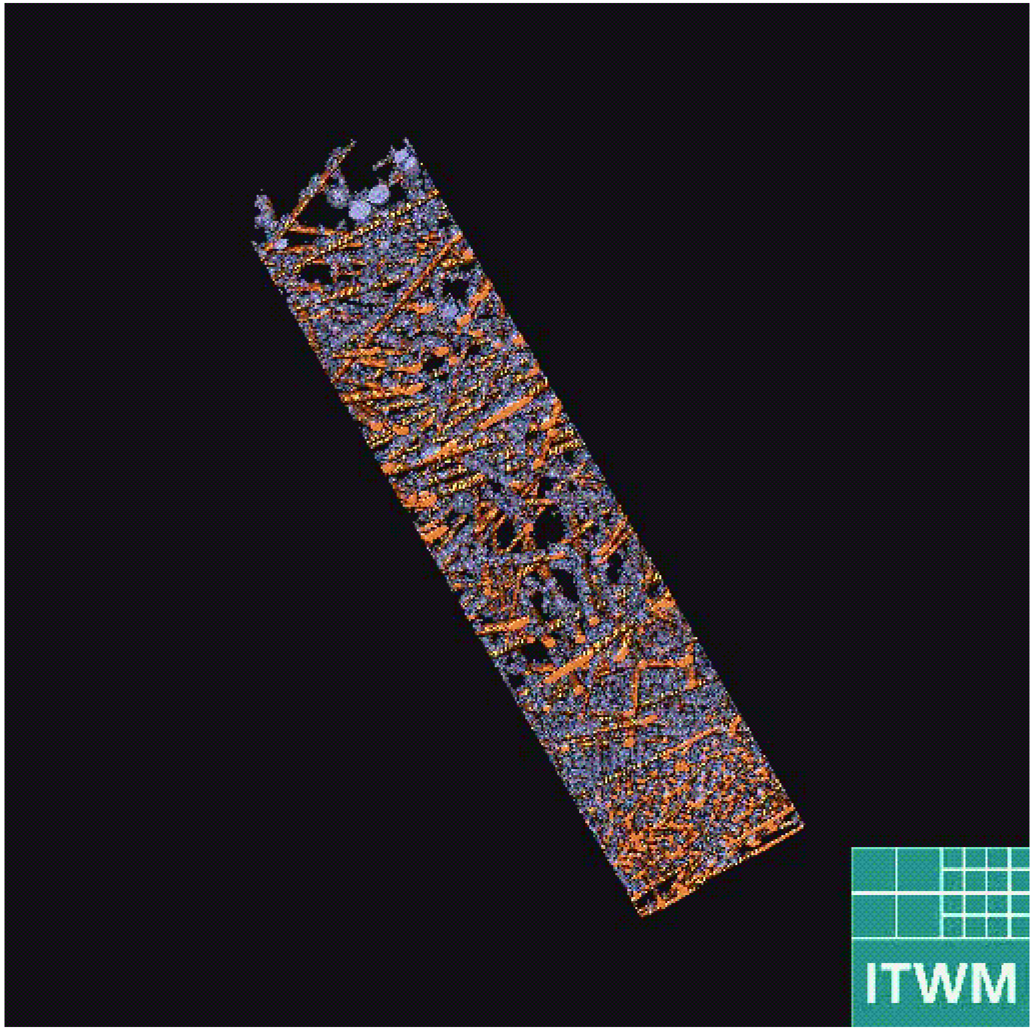
❖ Could do multipass by adjusting dirt model in every iteration

❖ Might have to recompute electric field after deposition

❖ Will reduce permeability based on nano-scale simulation (soot model)

Filter life time simulation: empty state and intial deposition





GEO DICT

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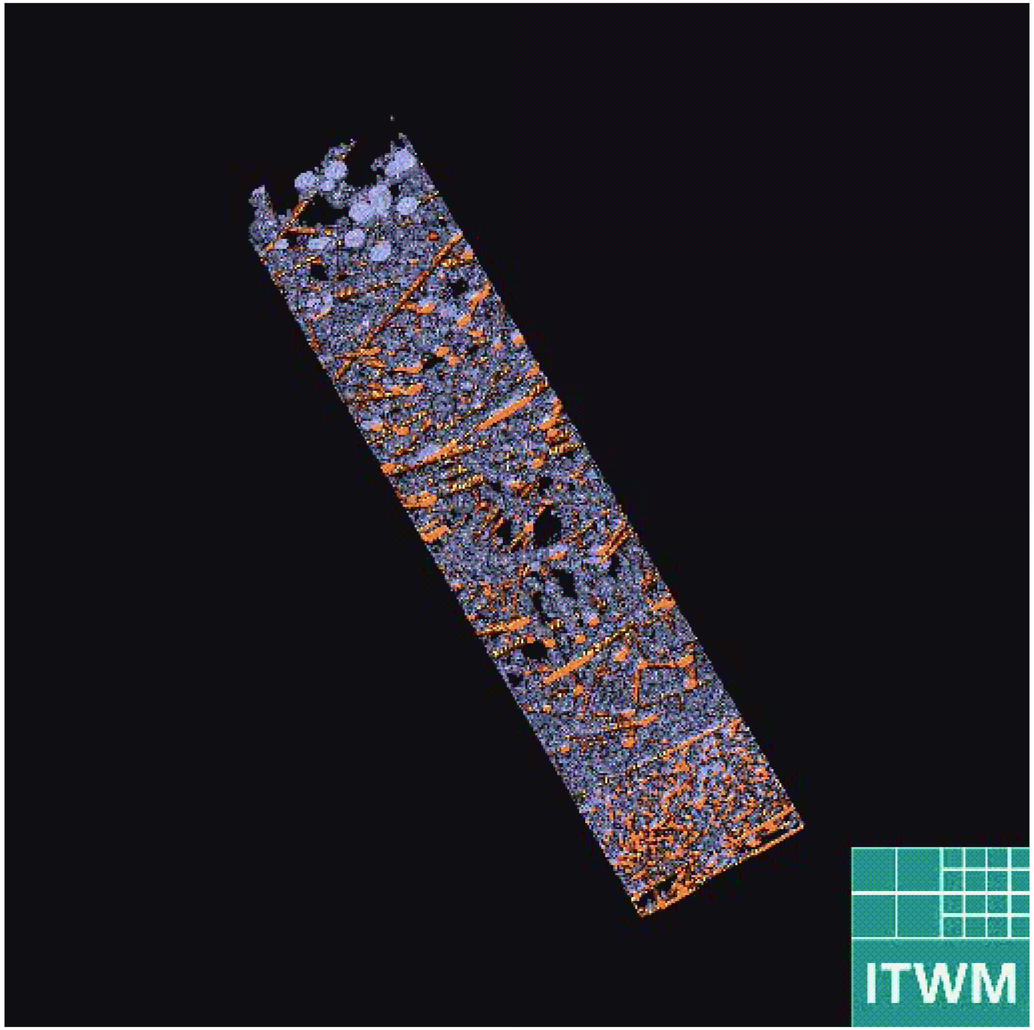
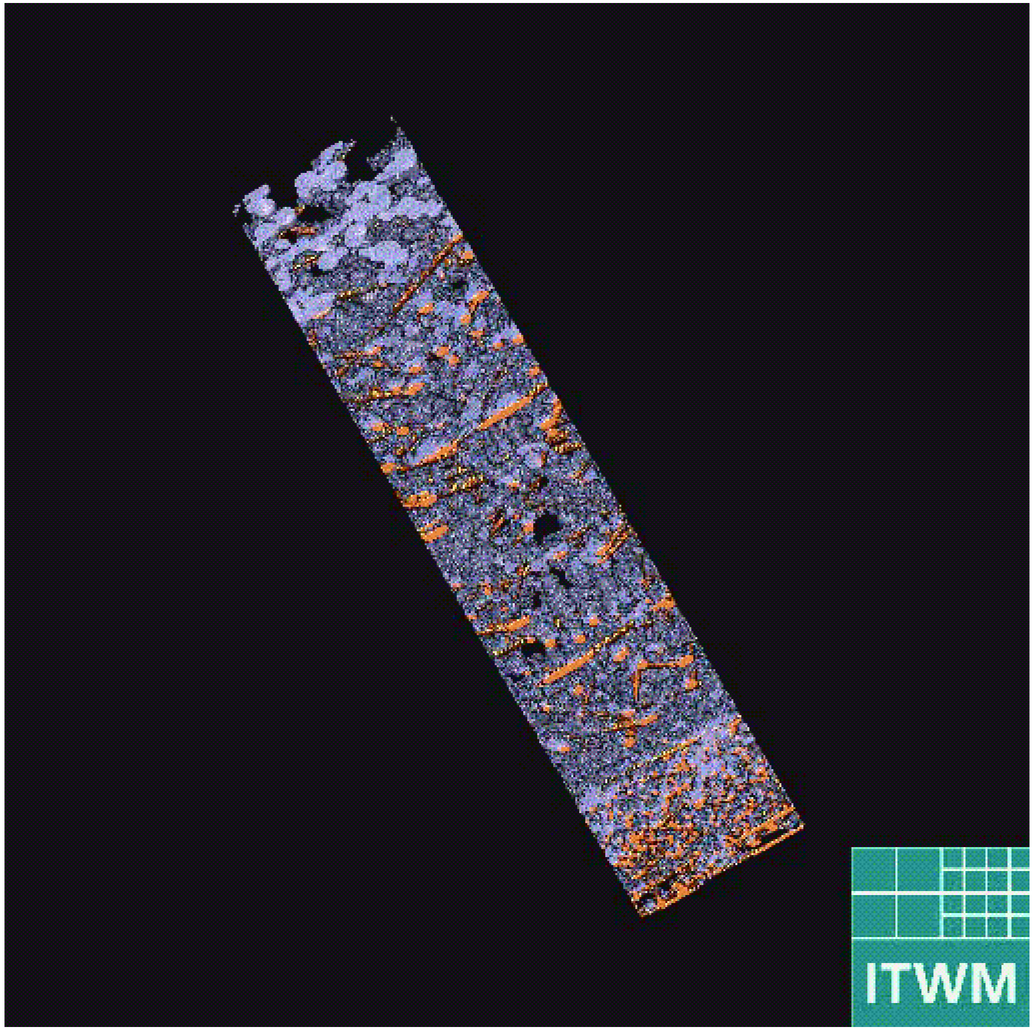
FCC, Gotenburg

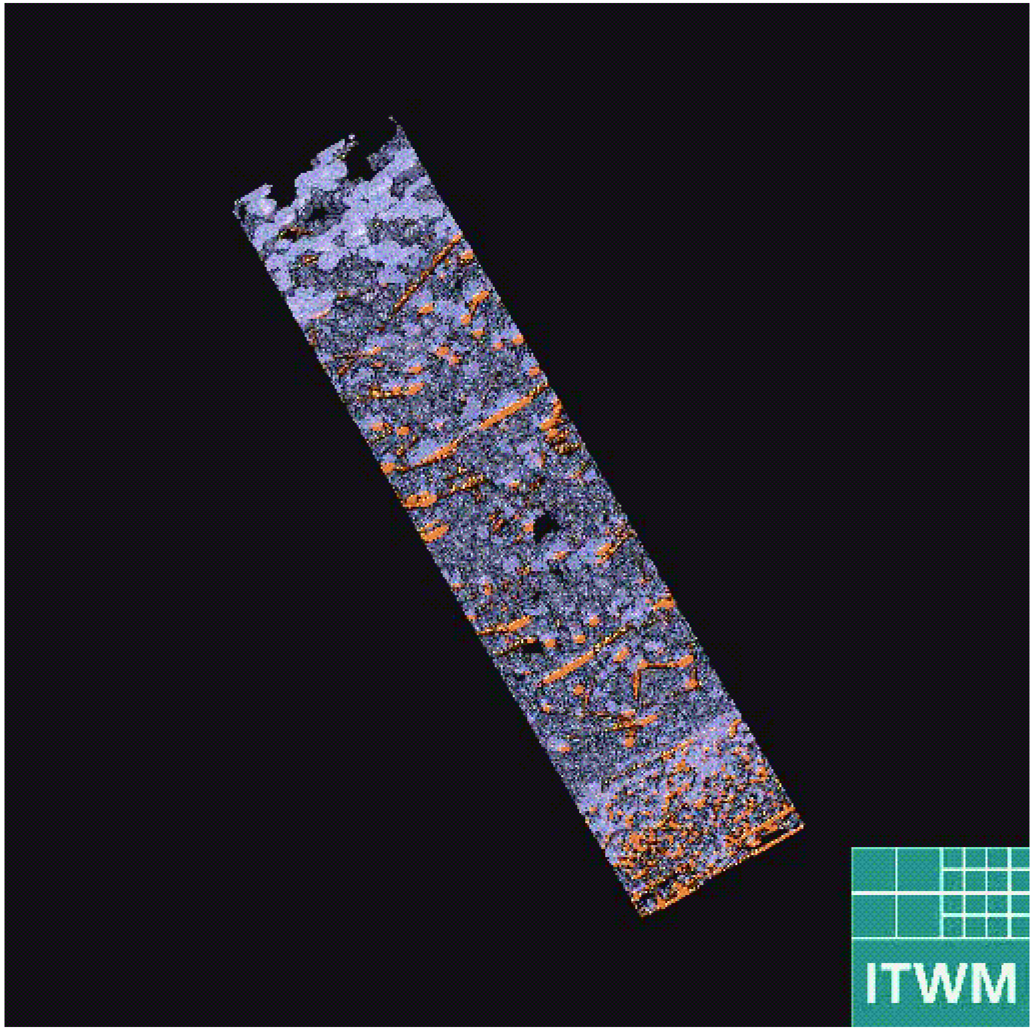
09 March 2005

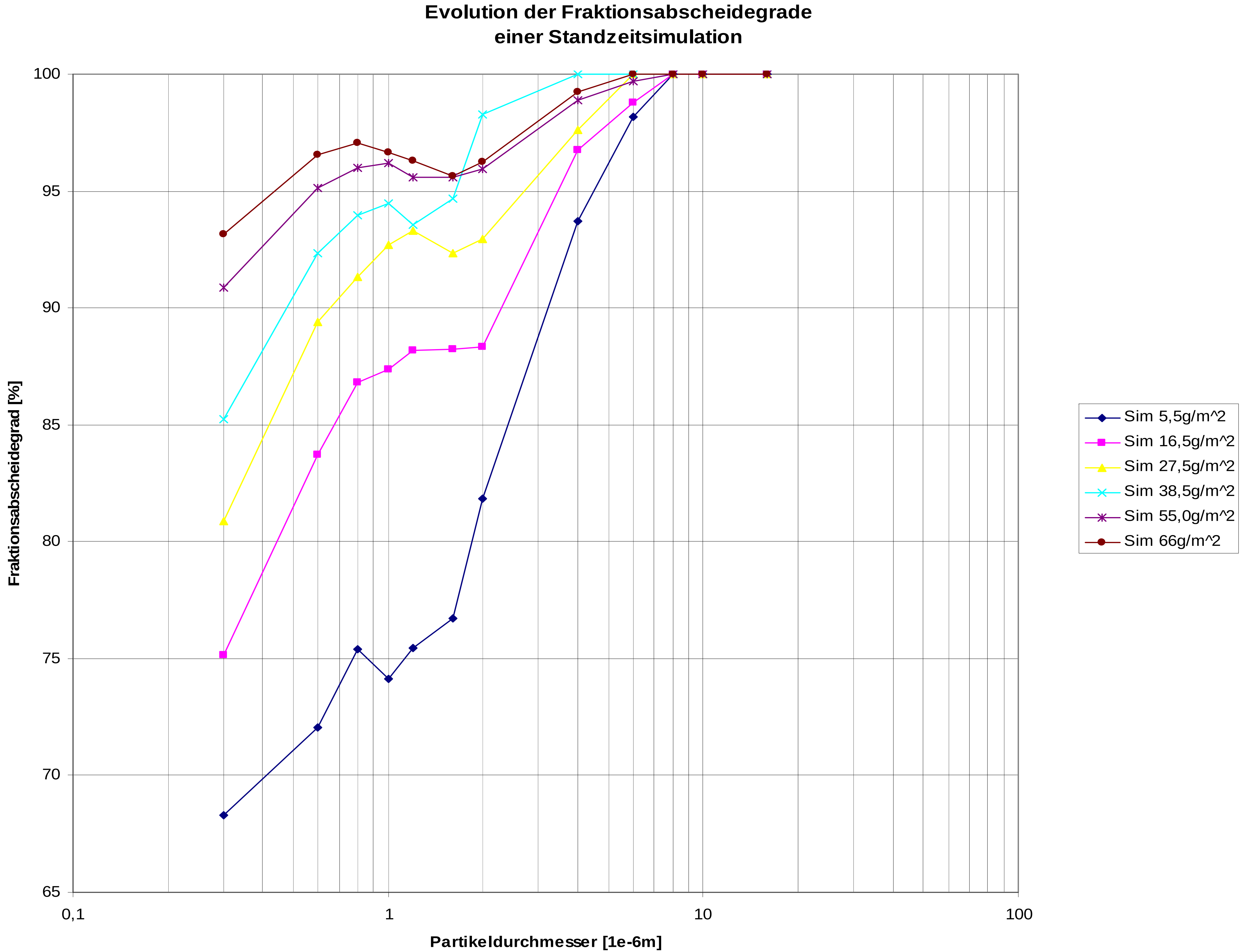
Filter life time simulation: states 3 and 4





Filter life time simulation: final state



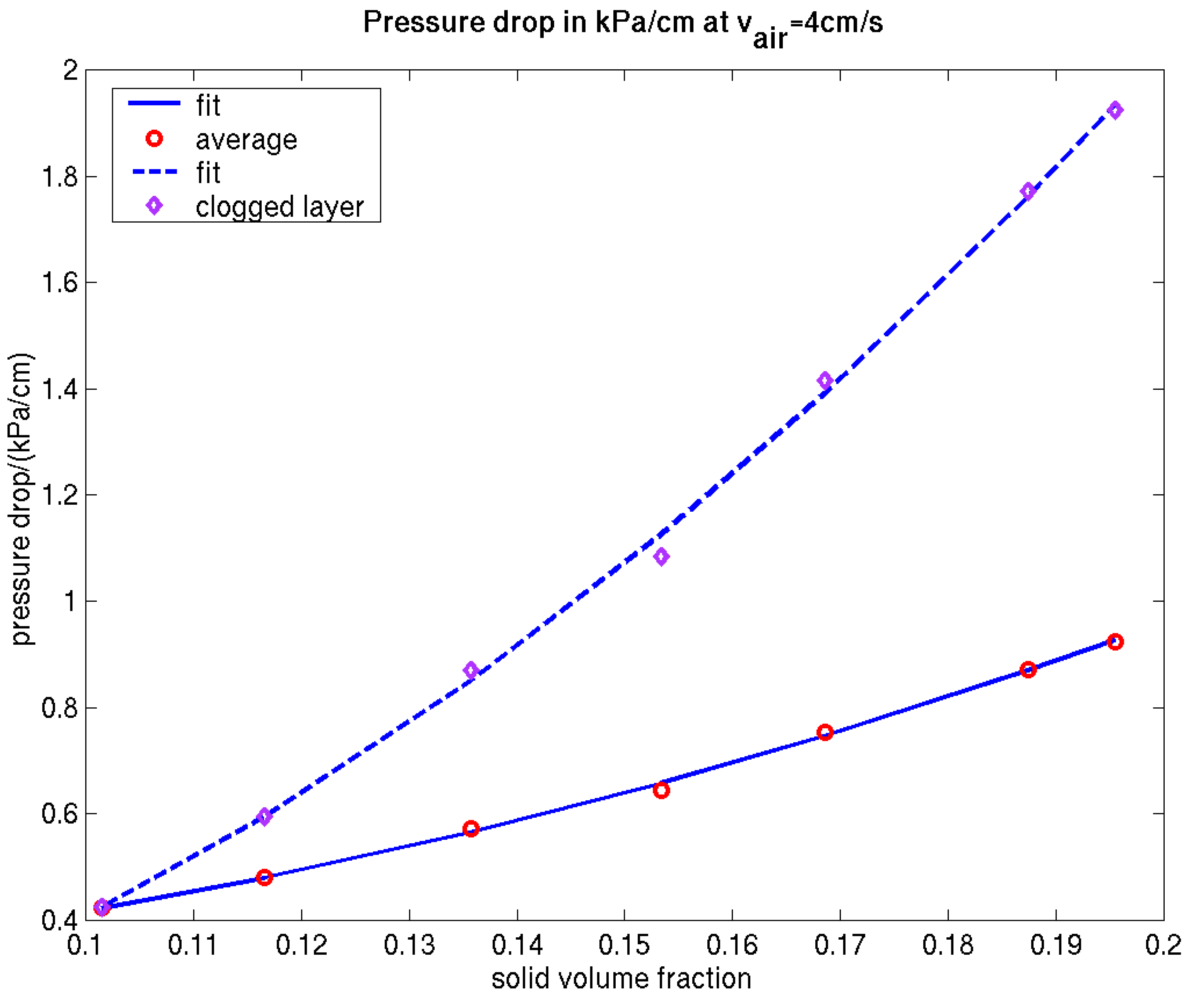


Evolution der Fraktionsabscheidegrade
einer Standzeitsimulation
Fraktionsabscheidegrad [%]
100
95
90
85
80
75
70
65
0,1
1
10
100
Partikeldurchmesser [1e-6m]
Sim 5,5g/m^2
Sim 16,5g/m^2
Sim 27,5g/m^2
Sim 38,5g/m^2
Sim 55,0g/m^2
Sim 66g/m^2

Time dependent pressure drop

- in the loaded portion of the media

- on average over the whole media



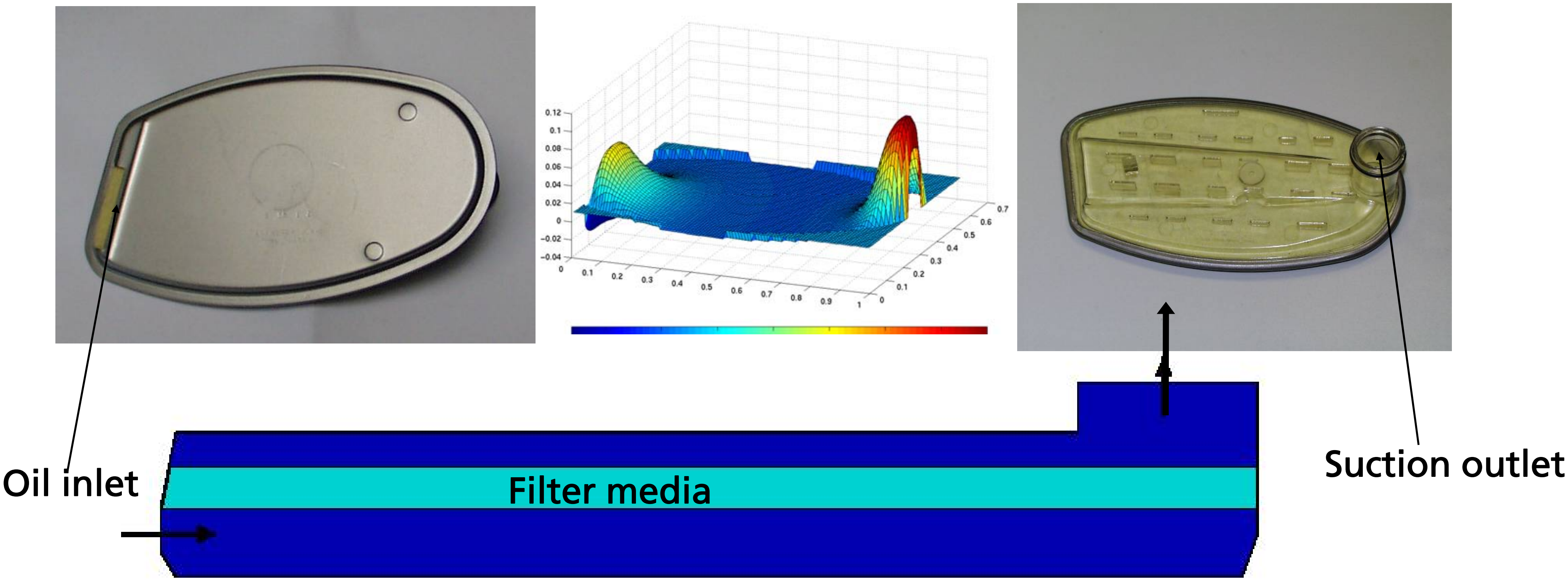
Virtual Filter media design with nonwovens:

- Define filtration parameters: geometry, polymer, dirt, fluid for existing media / standard test
- Compute filtration efficiency / filter life time, validate simulation based on existing nonwoven
- Vary filtration parameters and recompute filter efficiency / filter life time until simulation predicts the desired improvement
- Produce the new nonwoven and see that it works

Design of suction filters

Bottom of suction filter casing

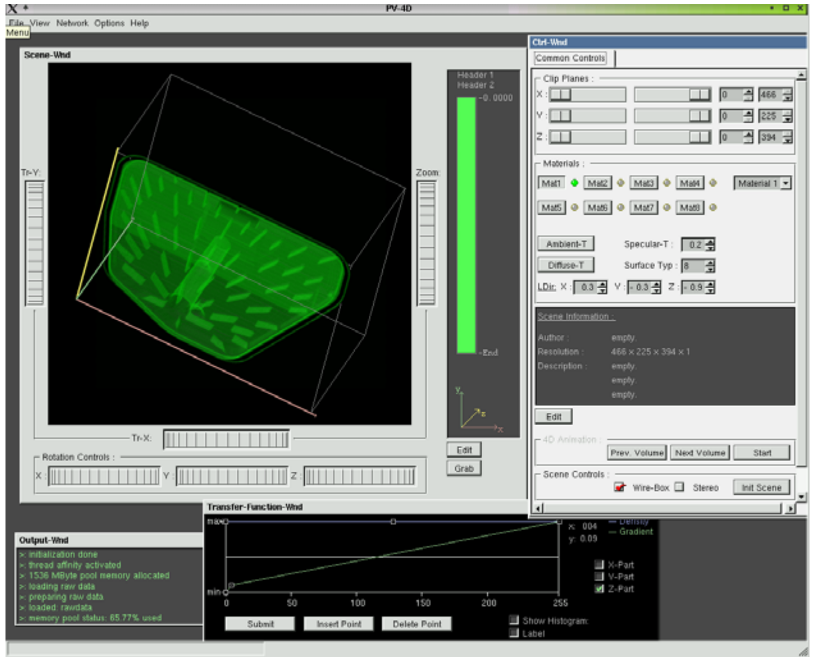
Top of suction filter casing

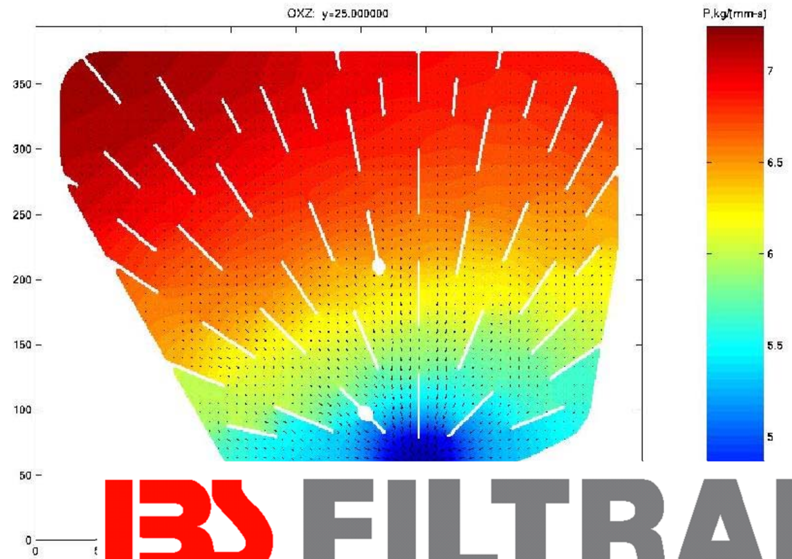


Goal: Optimization of filtration properties.

Suction Filter Simulation

- Simulation of the complete filter
- Efficient numerics for the coupled system: Navier-Stokes-Brinkmann
- Calculation of pressure and velocity in the filter including the filter media
- SuFiS: filter design software for transmission filters (SPX/IBS Filtran)
- Optimization of the filter casing, ribs, position of media
- Fully automatic grid from CAD (LevelDict)
- Visualization with PV4D





GEO DICT

FILTER DICT

ITWM

Fraunhofer Institut Techno- und Wirtschaftsmathematik

IBS FILTRAN

Summary

Filtration properties of filter media can be computed and optimized

1. 3d geometry from tomography or mathematical model
2. Model the fluid flow and the dirt as well as interaction, e.g. adhesion
3. MPPS: small particles filtered by diffusion, large ones by sieving
4. Layered materials give more uniform clogging, can have multiple properties
5. Study of electrostatic effects on pressure drop is on its way
6. Coupling with mechanical deformation (oil filtration) on ist way, next talk
7. Desktop version of FilterDict usable through ITWM's GeoDict software.
8. Virtual filter material design is possible!