Concepts for Modelling Filter Media and Simulating Filtration Processes

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GeoDict

MATH 2 MARKET

Thanks to collaborators at Math2Market, Fraunhofer ITWM, and elsewhere

Math2Market:

- Mehdi Azimian, Jürgen Becker, Liping Cheng, Erik Glatt, Barbara Planas, Christian Wagner, Rolf Westerteiger.

ITWM:

- Heiko Andrä, Oleg Iliev, Mathias Kabel, Ralf Kirsch, Peter Klein, Sven Linden, Stefan Rief, Katja Schladitz, Konrad Steiner, Aivars Zemitis.

Formerly at ITWM:

- *D. Elvikis, I. Ginzburg, D. Kehrwald, Z. Lakdawala, A. Latz, J. Ohser, D. Reinel-Bitzer, V. Rutka, K. Schmidt, A. Kumar Vaikuntam, Q. Zhang.*

Others:

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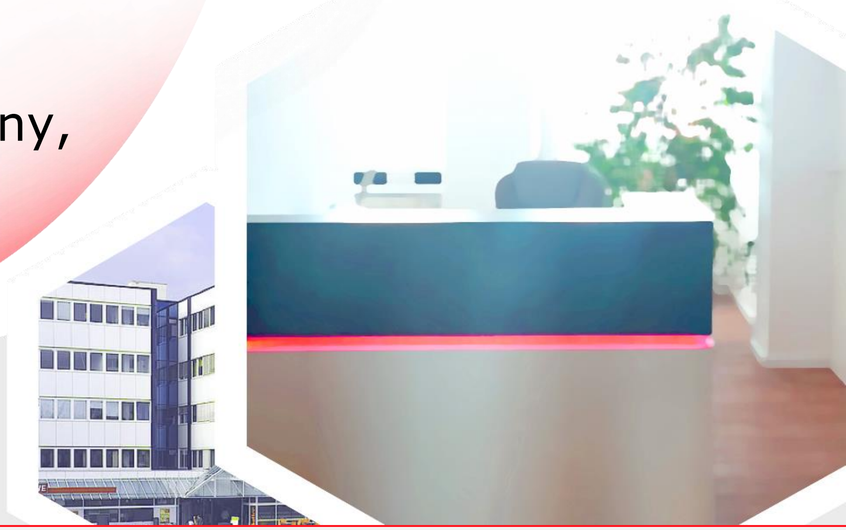
- Friedrich Edelmeier, Frank Meyer, Mirko Theiß & Alexander Mantler of **Haver & Boecker**
- Graham Rideal, **Whitehouse Scientific**
- *Andreas Schindelin*, then of **Argo-Hytos GmbH**
- Jörg Adler, Uwe Petasch & *Lars Mammitsch* of **Fraunhofer IKTS**
- *S. Jaganathan* & *H. Tafreshi*, then at ***Nonwoven Cooperative Research Center, NC***
- Nathalie Bardin-Monnier & *Pierre-Colin Gervais*, then at **Nancy University**

Math2Market GmbH and its GeoDict software
Some background information

- Math2Market creates & markets software to analyze/design porous & composite materials based on the material's geometric inhomogeneity
- M2Ms software is called GeoDict, the Digital Material Laboratory
- GeoDict works on µCT-based, FIB-SEM-based and intrinsic models - in all cases, the computer representation consists of 3-D images
- M2M was spun off in 2011 from Fraunhofer Institute for Industrial Mathematics
- M2M is based in Kaiserslautern, Germany, and privately owned
- M2M has more than 150 clients from around the world



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Math2Market GmbH
Promoted Industries

Filtration	Mostly automotive, filter media & filters for water, sludge, oil, air and fuel
Electrochemistry	Fuel cell media & battery materials, catalyst materials
Composites	CFRP, GFRP, mostly automotive, lightweight materials
Oil and Gas	Digital rock physics, digital sand control

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AFS 2017, Louisville
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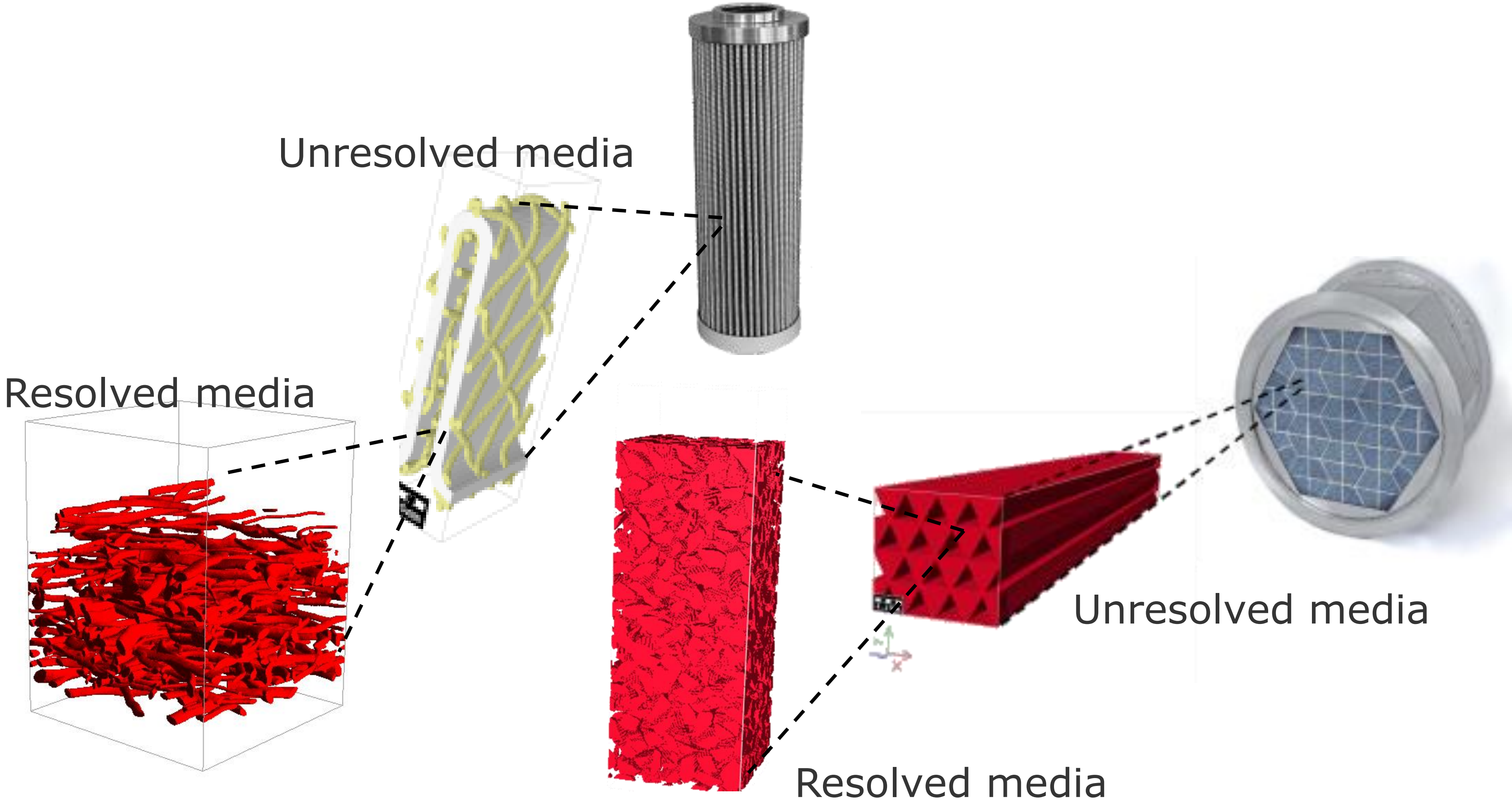
About the need for modelling and simulation

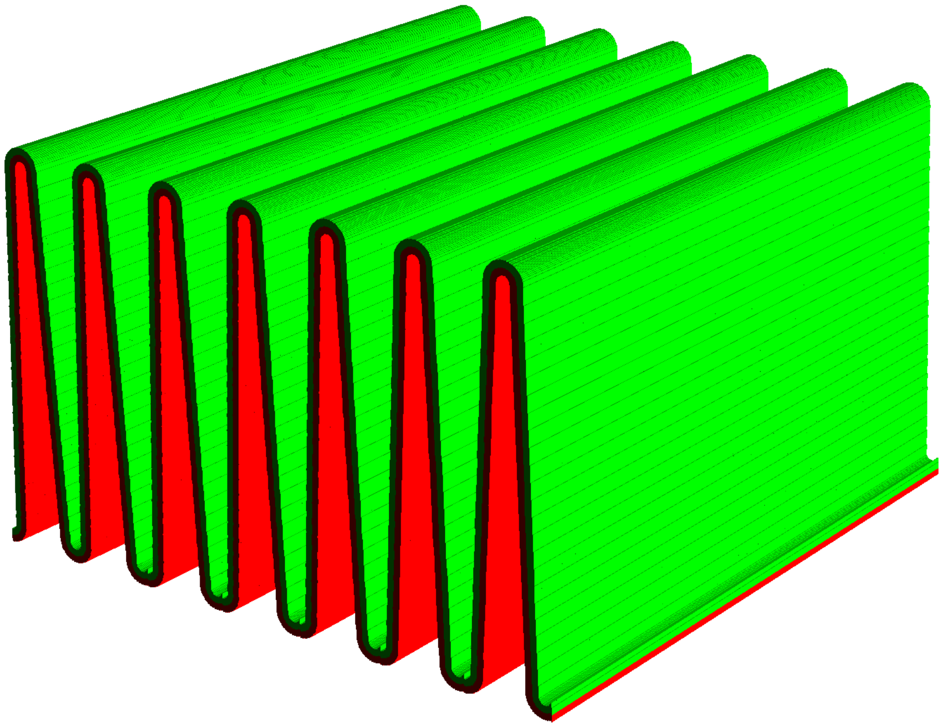
- The function of porous and composite materials results from the choice of raw materials and their micro structure, i.e. the distribution of the constituents, e.g. fibers, in space.
- The power of simple models to predict the effects of the micro structure is limited.
- µCT and FIB-SEM provide 3D images of existing materials with unprecedented resolution.
- From these, one can compute the material's properties to match measured properties.
- Models also convert into 3D images. From these, material properties can be determined without the need to manufacture the new materials first.
- Instead of letting universities or institutes develop next generation materials, companies keep this knowledge in-house, by letting their own employees run the digital experiments.
- The Difficulty of the Math & Software Know-How is such that even the largest companies cannot do it all by themselves.
- 10 of the top 100 market capitalized companies are M2M clients, including Shell and P&G, who introduced the concept of open innovation about 2 decades ago.
- In the future, companies will need to be on top of their materials. The days of trial and error are coming to an end as powerful research tools deliver scientific data of unprecedented depth. [http://www.economist.com/technology-quarterly/2015-12-05/new-materials-for-manufacturing]
- At M2M, we believe this is true in particular for filter media – the future has already begun!

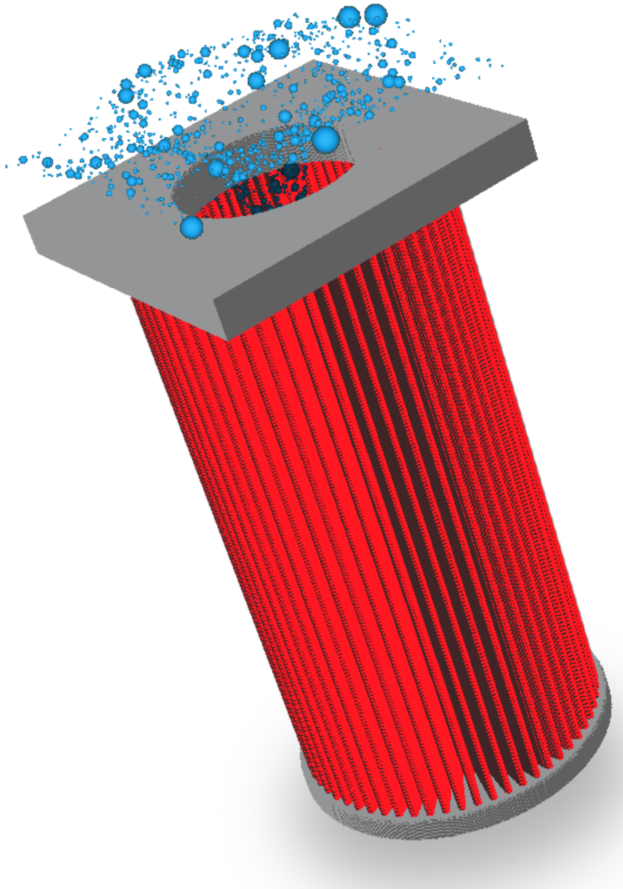
Media models, pleat models and filter models

Simulate filtration at different scales



Create Pleat scale and Element scale models



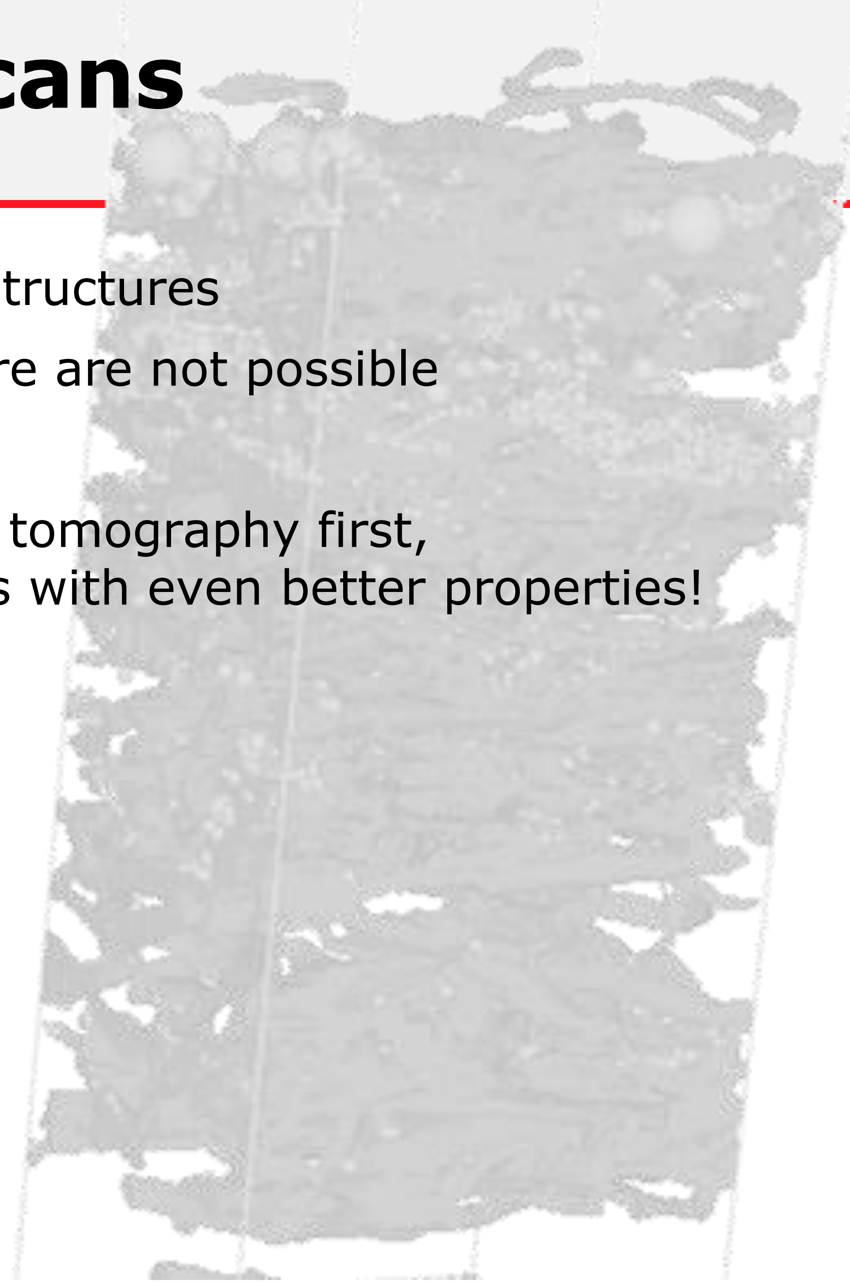


Simulate on μCT scans

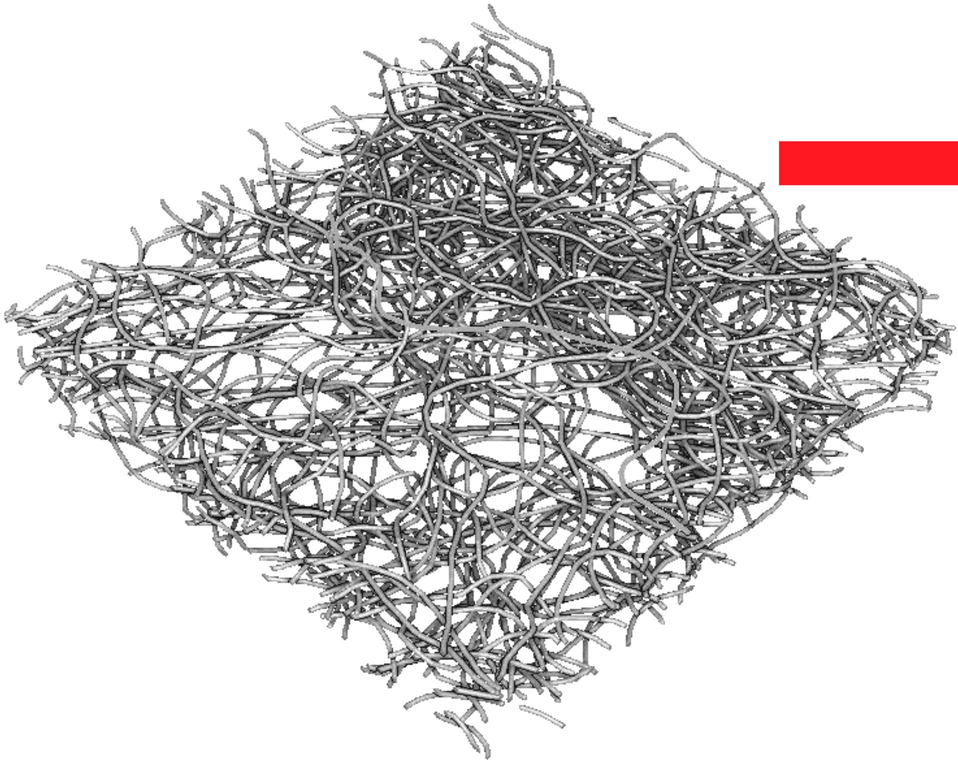
(+) Allows simulations on real filter structures

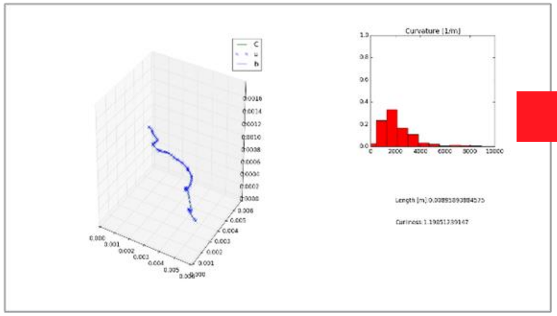
(-) Modifications of the filter structure are not possible

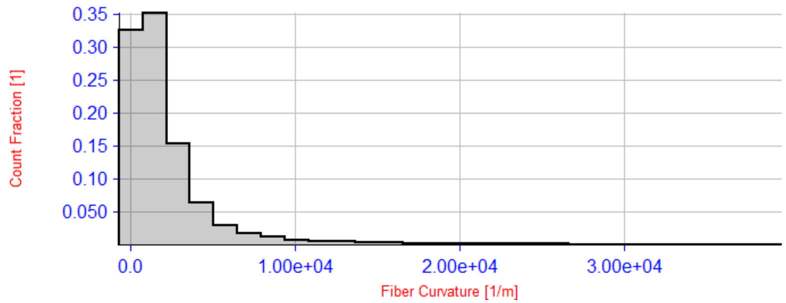
Aim: create a model that mimics the tomography first,
then modify it to find structures with even better properties!



3. Fiber Curvature





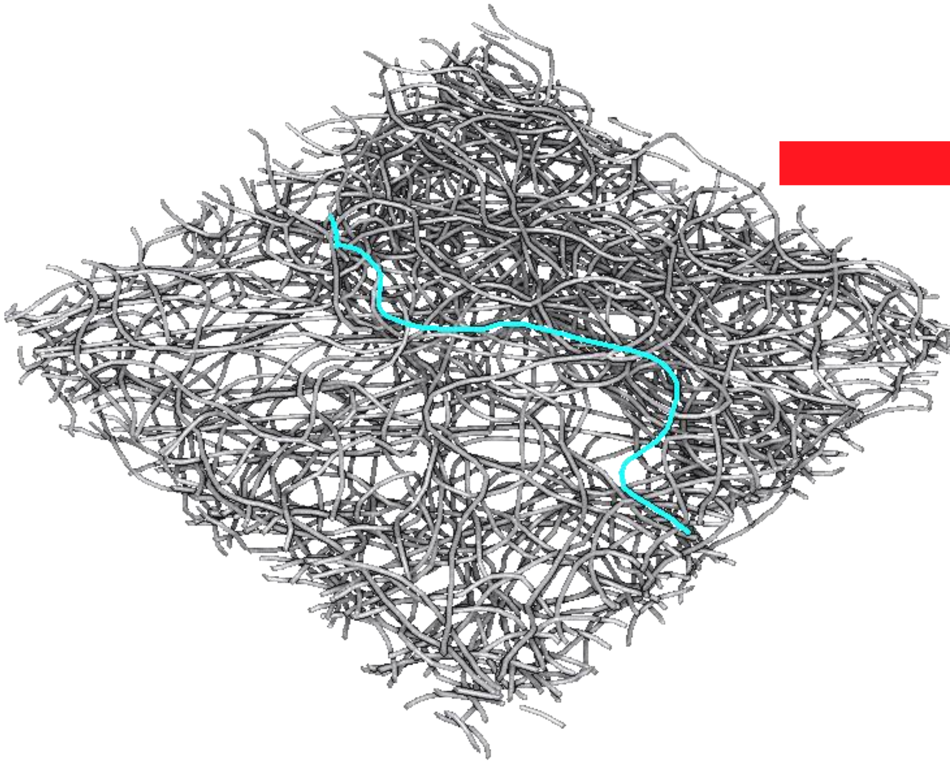


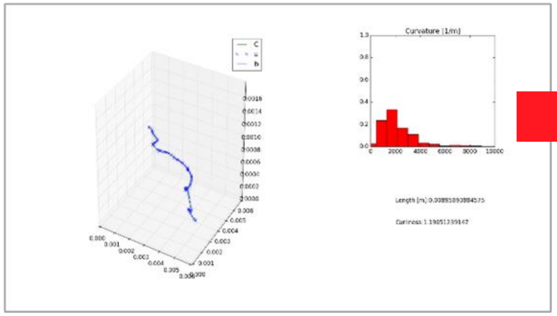
Segment image

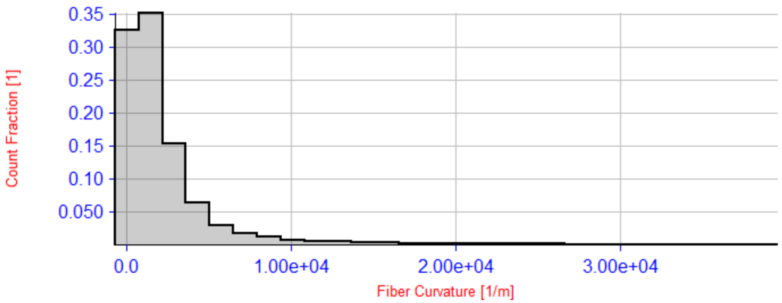
Identify fibers

Analyze every fiber individually and combine

3. Fiber Curvature



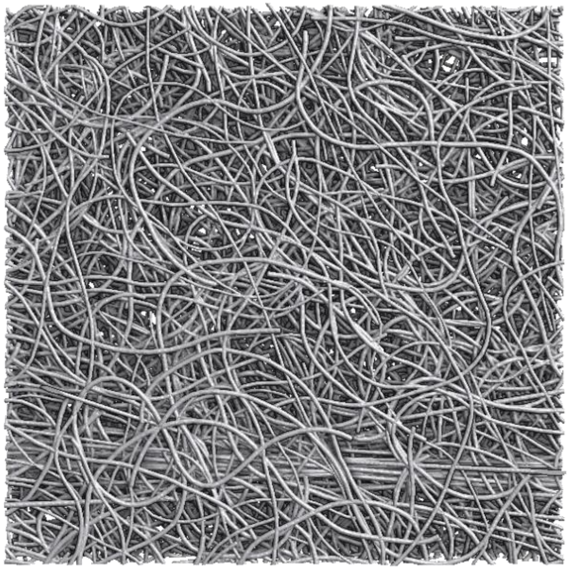




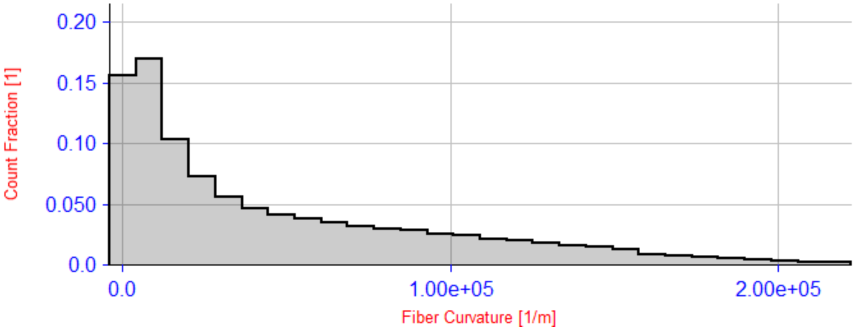
Segment image → Identify fibers → Analyze every fiber individually and combine

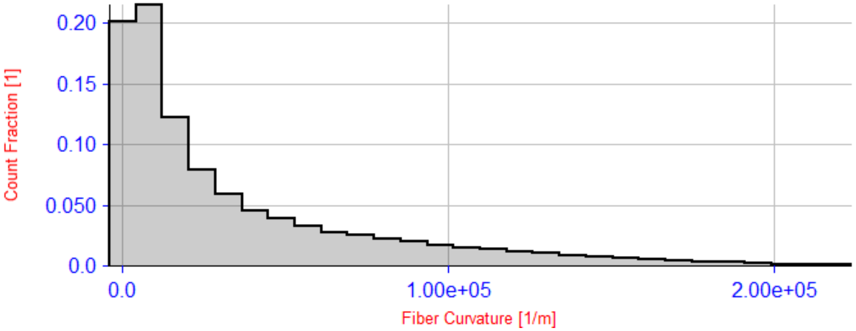
Estimated parameters used to generate a model of the gas diffusion layer

Original structure



Modeled structure

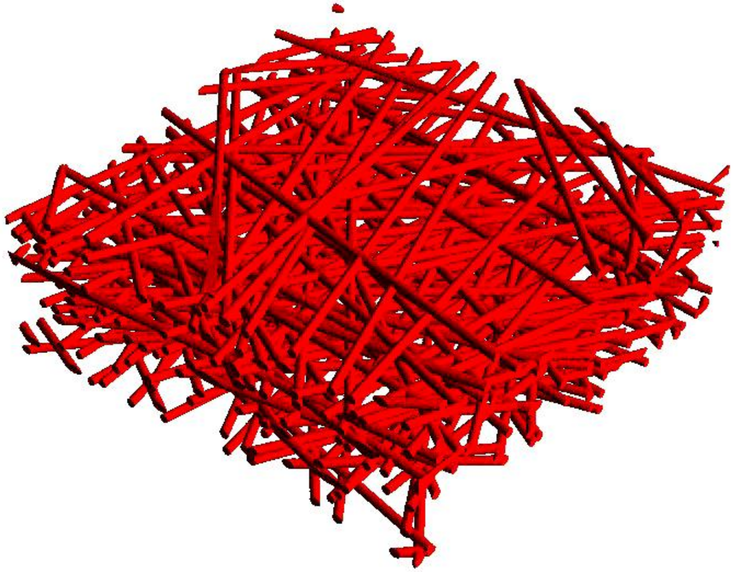




Create 3D structure models

Input parameters needed (straight fibers):

- Porosity
- Fiber type: cross sectional shape, diameter, length
- Fiber orientation tensor
- Thickness (height) of the filter media

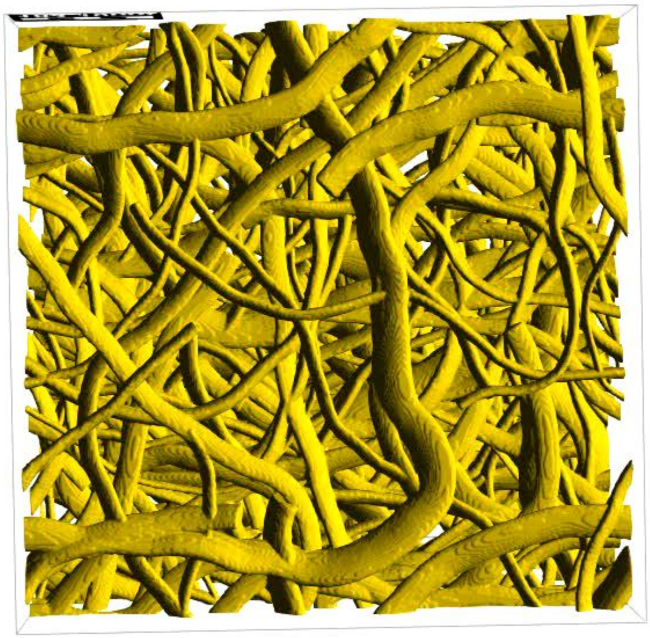


Parameters might be

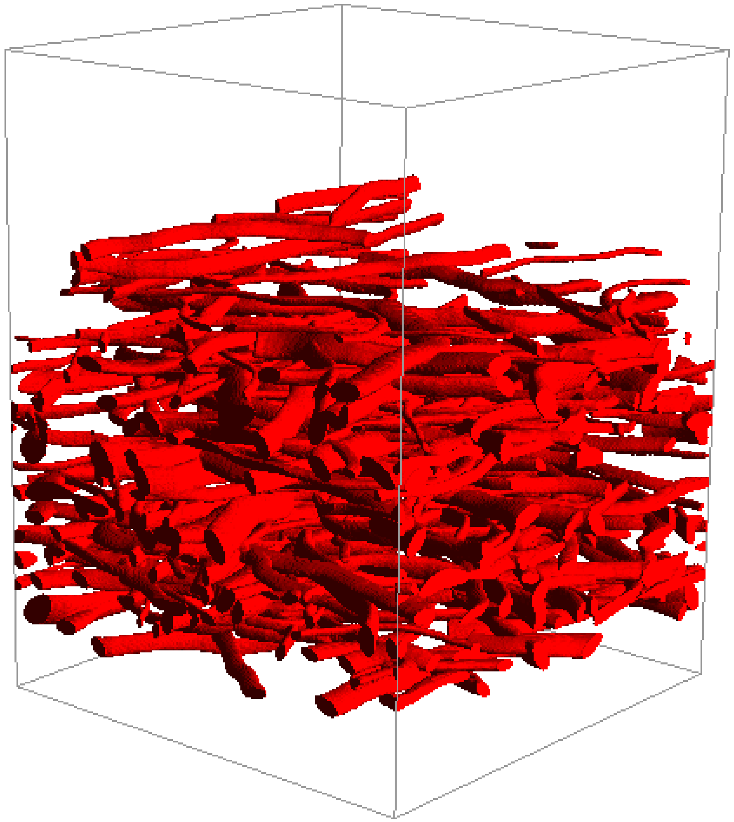
- known from manufacturing process
- measured experimentally
- measured from CT image

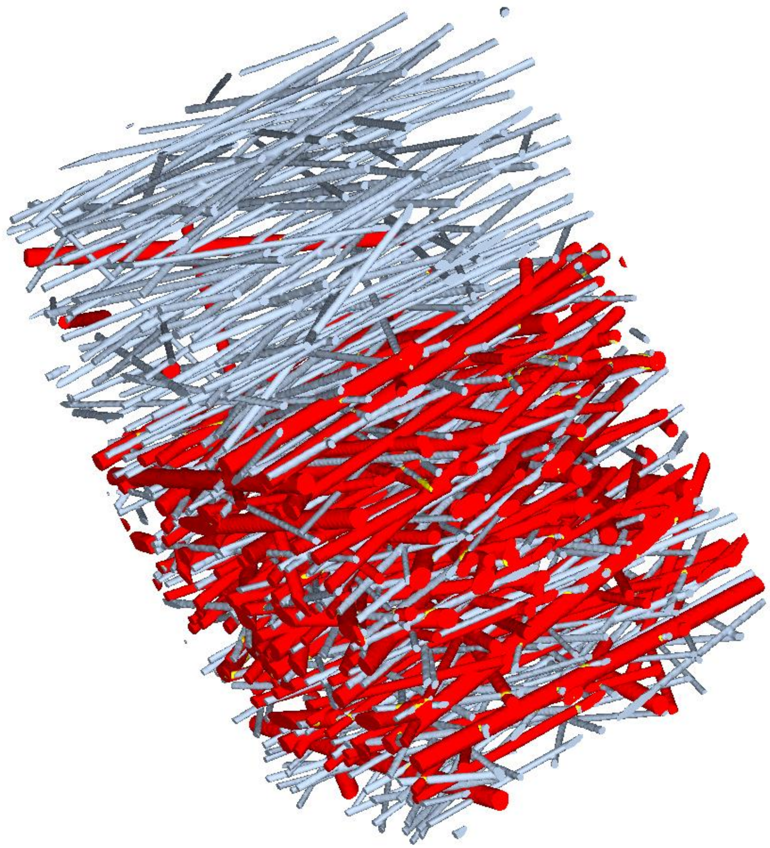
Create an oil filter model

- Ellipsoidal cross section, diameter distribution
- Curved fibers
- Fibers oriented in xy-plane
- 500 x 500 x 650 grid cells, 1 µm voxel length



Create cellulose and layered media scale models

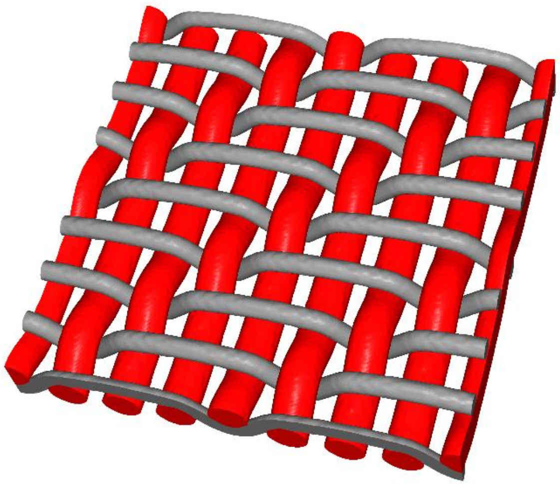


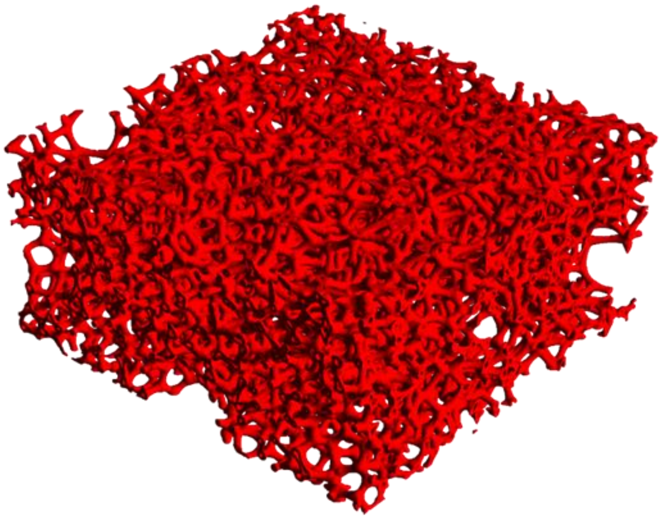


Cellulose nonwoven

Layered filter medium

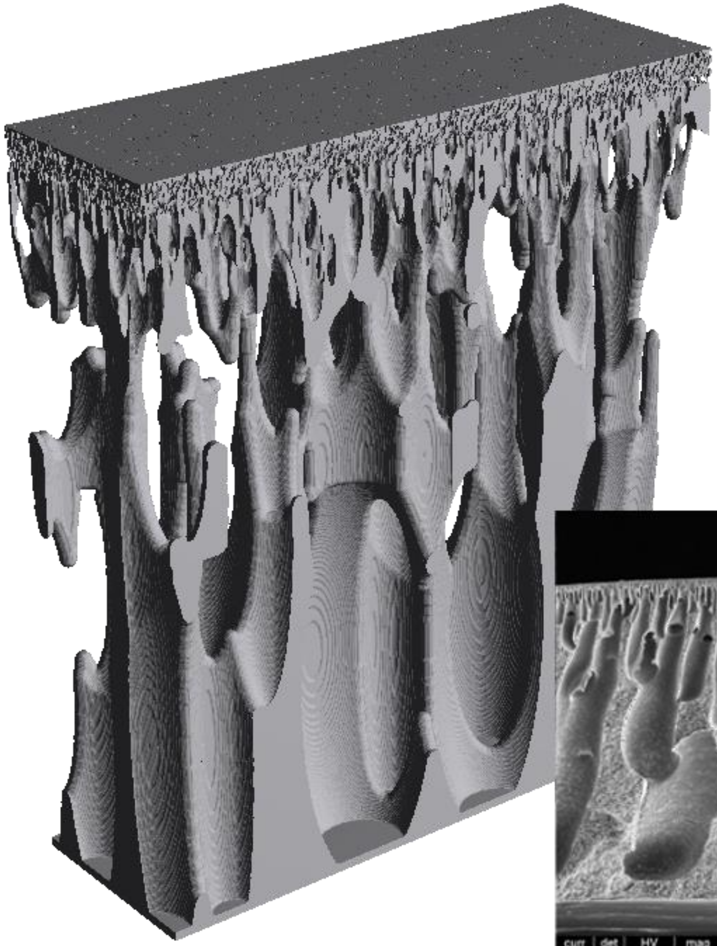
Create woven, foam and sintered media scale models

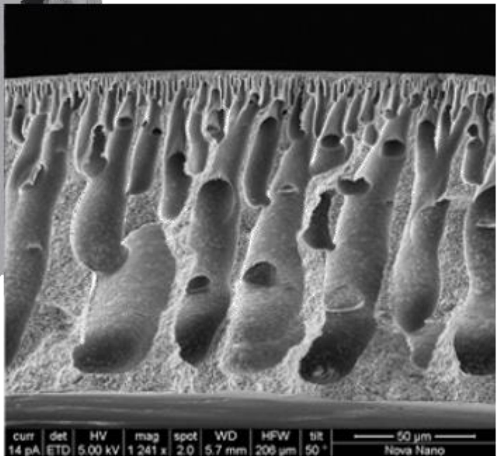




Metal wire mesh | Open-cell foam | Sintered ceramics

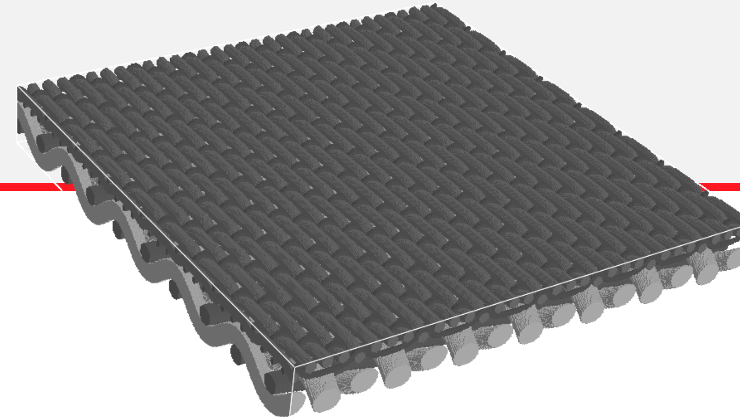
Model a desalination membrane from a SEM image



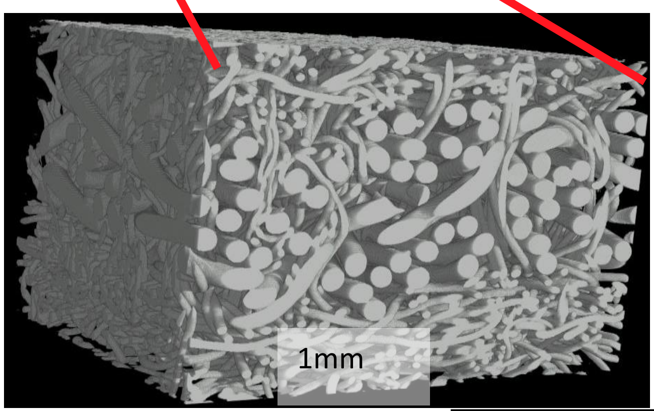


http://www.geodict.com/Showroom/structures.php

µCT scan and models of felts

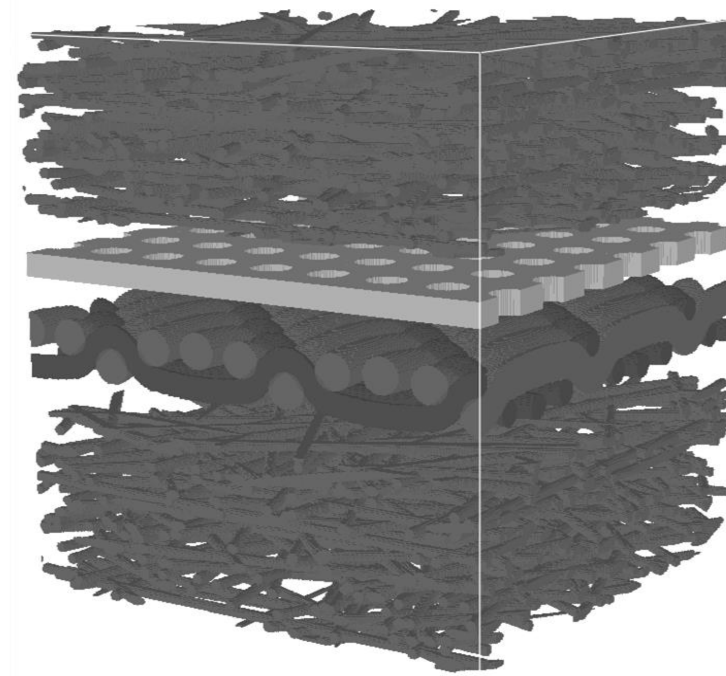


Paper machine



Tomography

Forming fabric and dewatering felt



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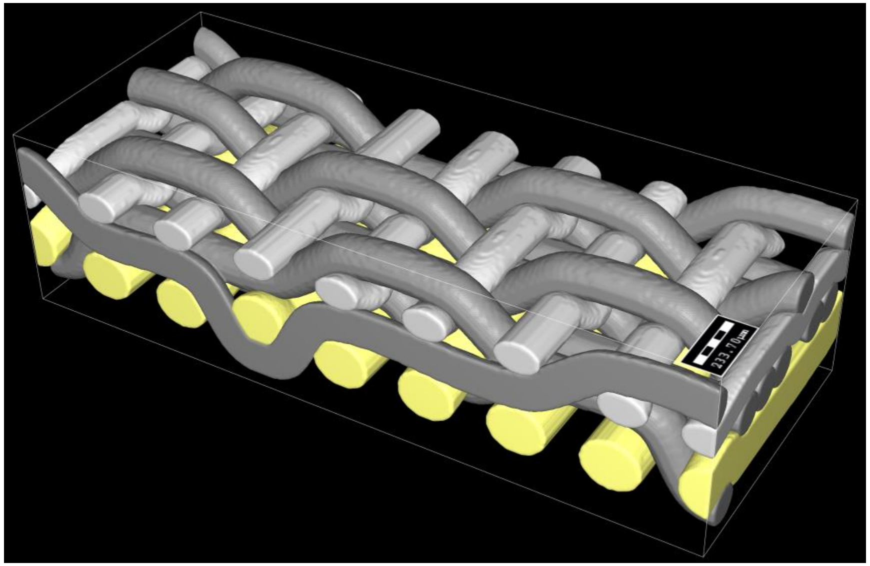
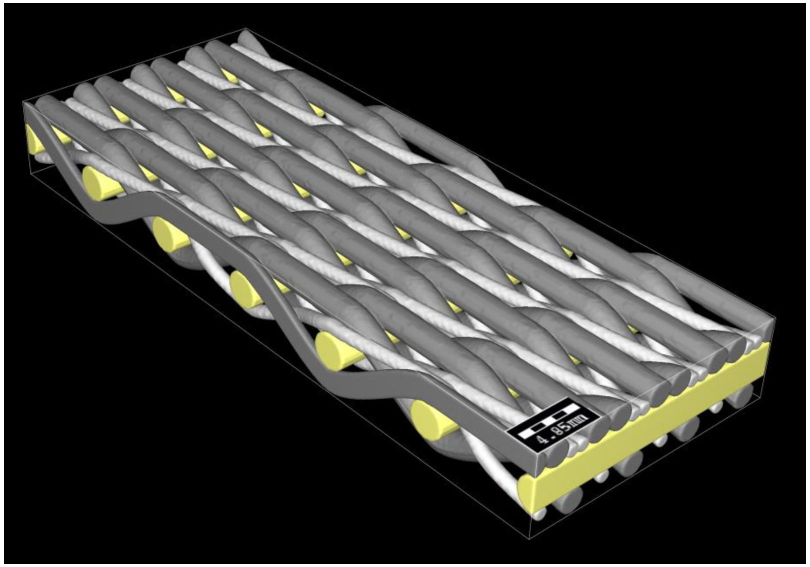
Woven Metal Wire Meshes: Complex weave models

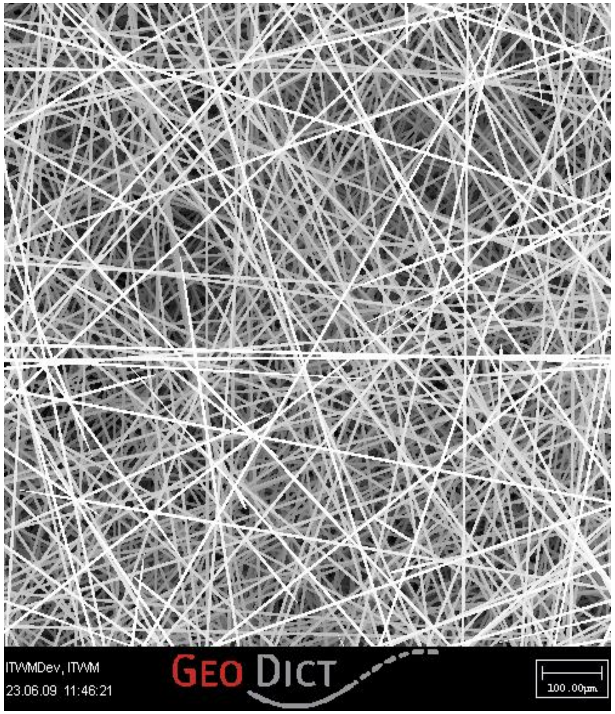




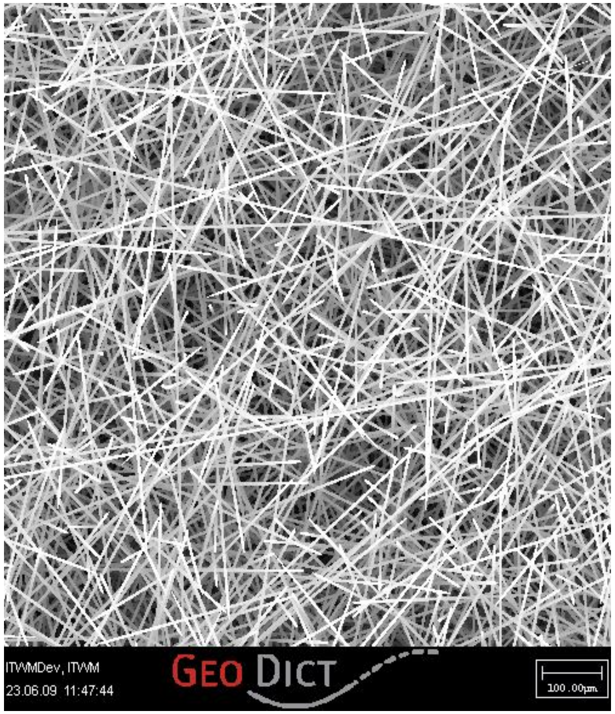
Left: Model of a two-layer weave based on a CT-scan.
Right: Model of a complex one-layer twill Dutch-weave.

Glass fiber nonwoven

SEM visualization of 8 volume percent 5 micron fibers

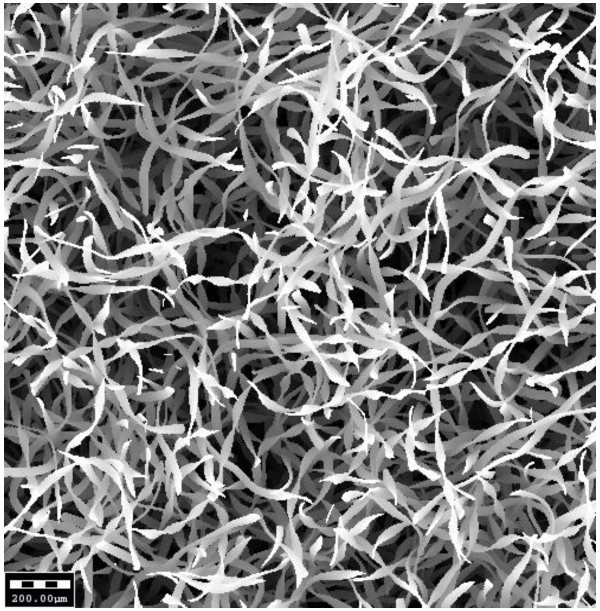


anisotropy 100

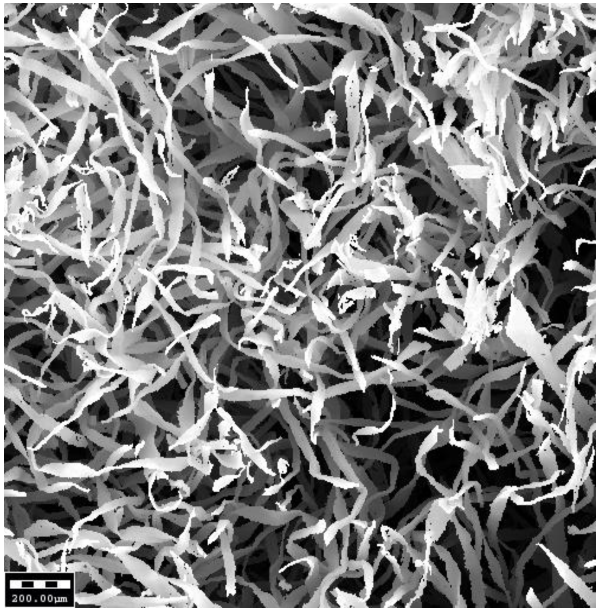


anisotropy 7

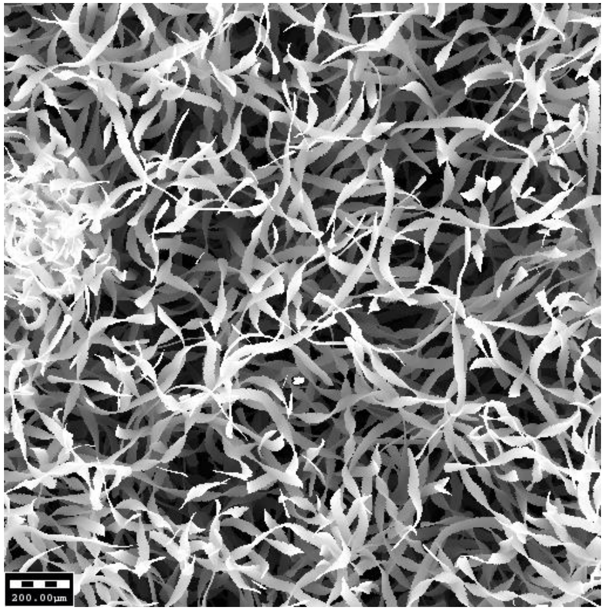
Curled & inhomogeneous <u>nonwoven</u>



homogeneous model

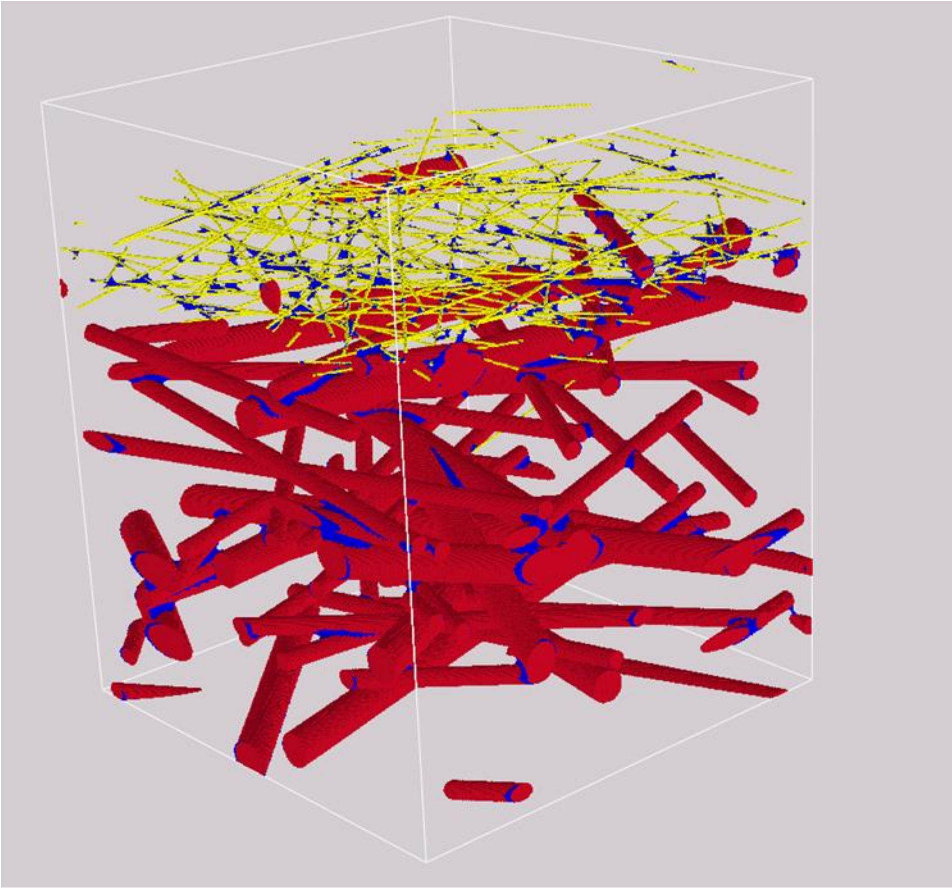


µCT scan



inhomogeneous model

Nonwoven with binder and layer of nano fibers



L. Cheng et al., Filtech 2009.

5.0 µm fibers (red)

2.5 µm fibers (red)

0.3 µm fibers (yellow)

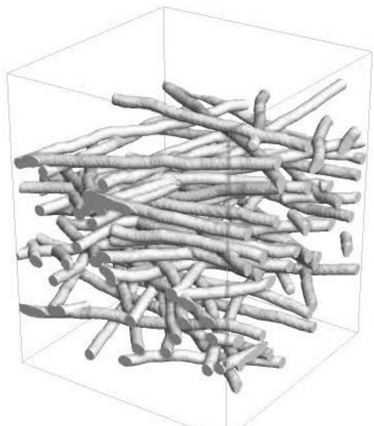
2 vol % binder (blue)

Oil Filtration: Simulation of Filter Life Time and Dust Holding Capacity Improved Modeling of Filter Efficiency Simulations

- Jürgen Becker, Andreas Wiegmann
  Math2Market GmbH, Kaiserslautern, Germany
- Friedemann Hahn, Martin J. Lehmann
  MANN+HUMMEL GMBH, Ludwigsburg, Germany

- Originally presented at Filtech

Particulate flow simulations



1. Filter model

2. Flow field

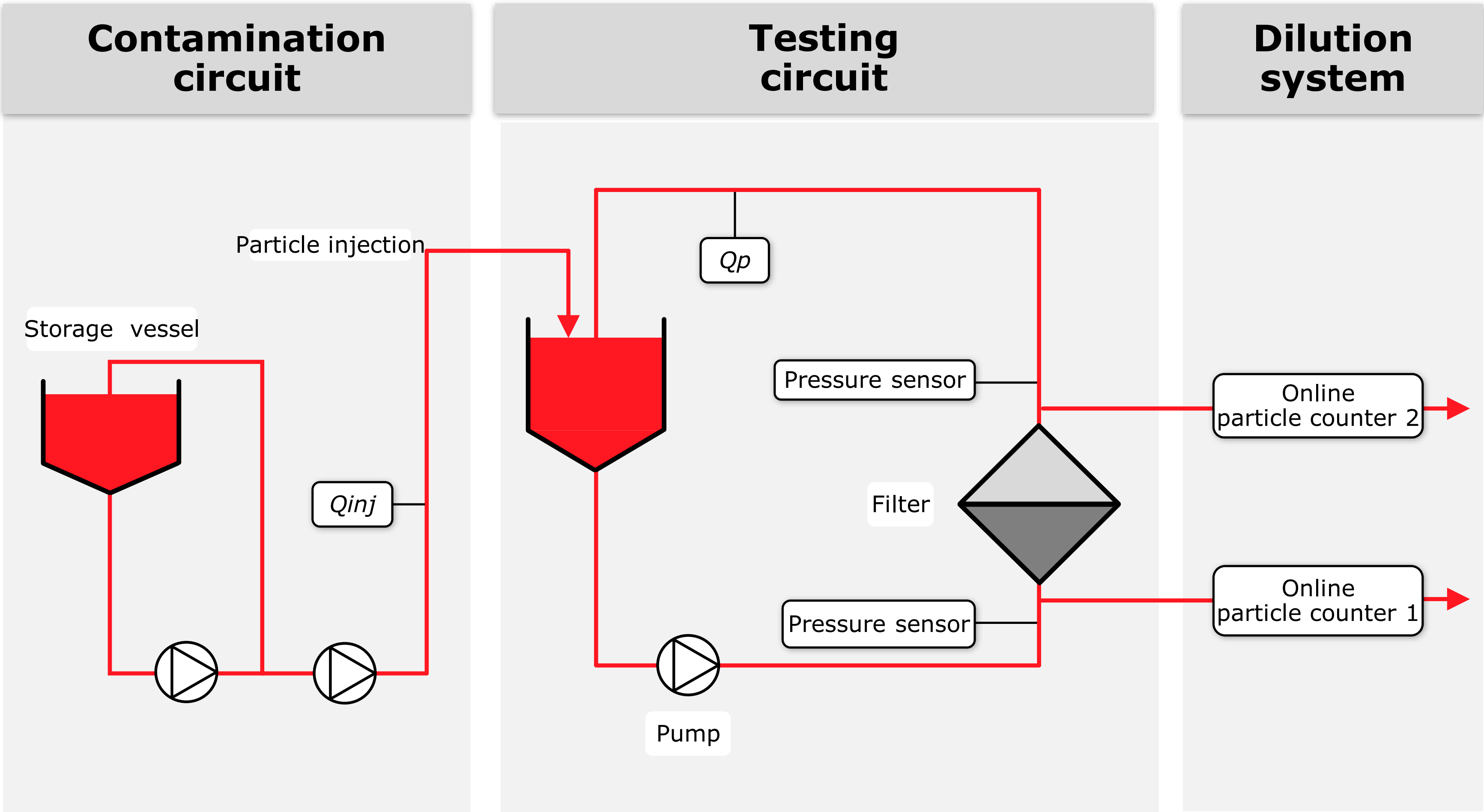
3. Track particles

4. Deposit particles

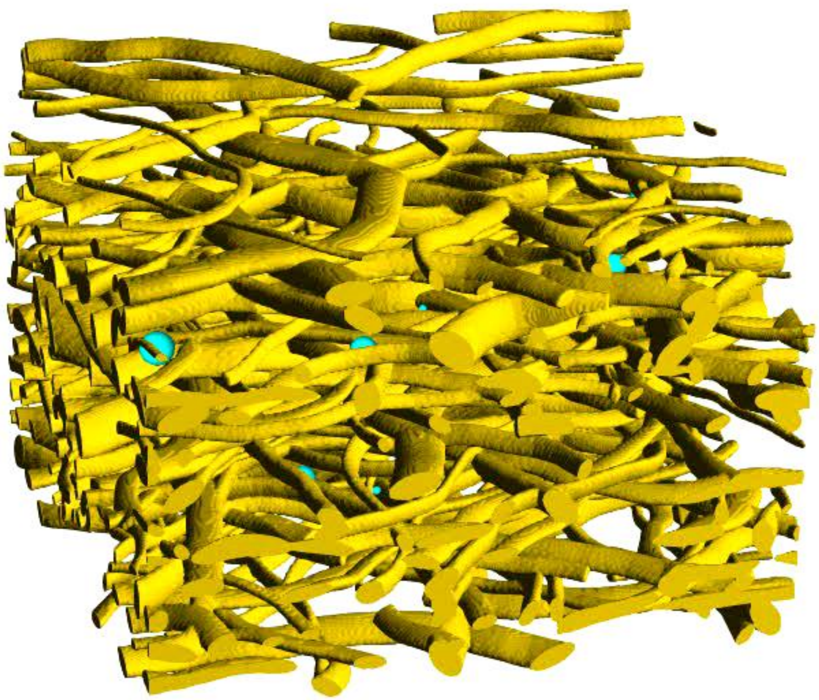
5. Flow field

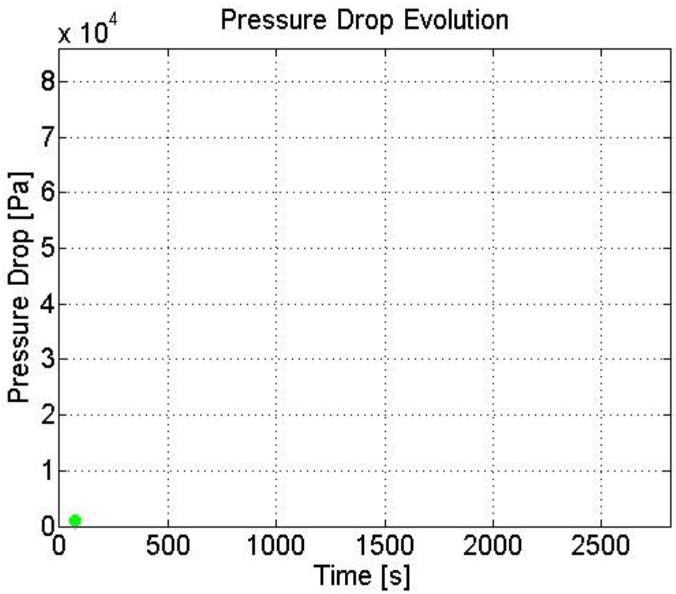
6. Repeat ...

The Multipass Test (ISO 4548)



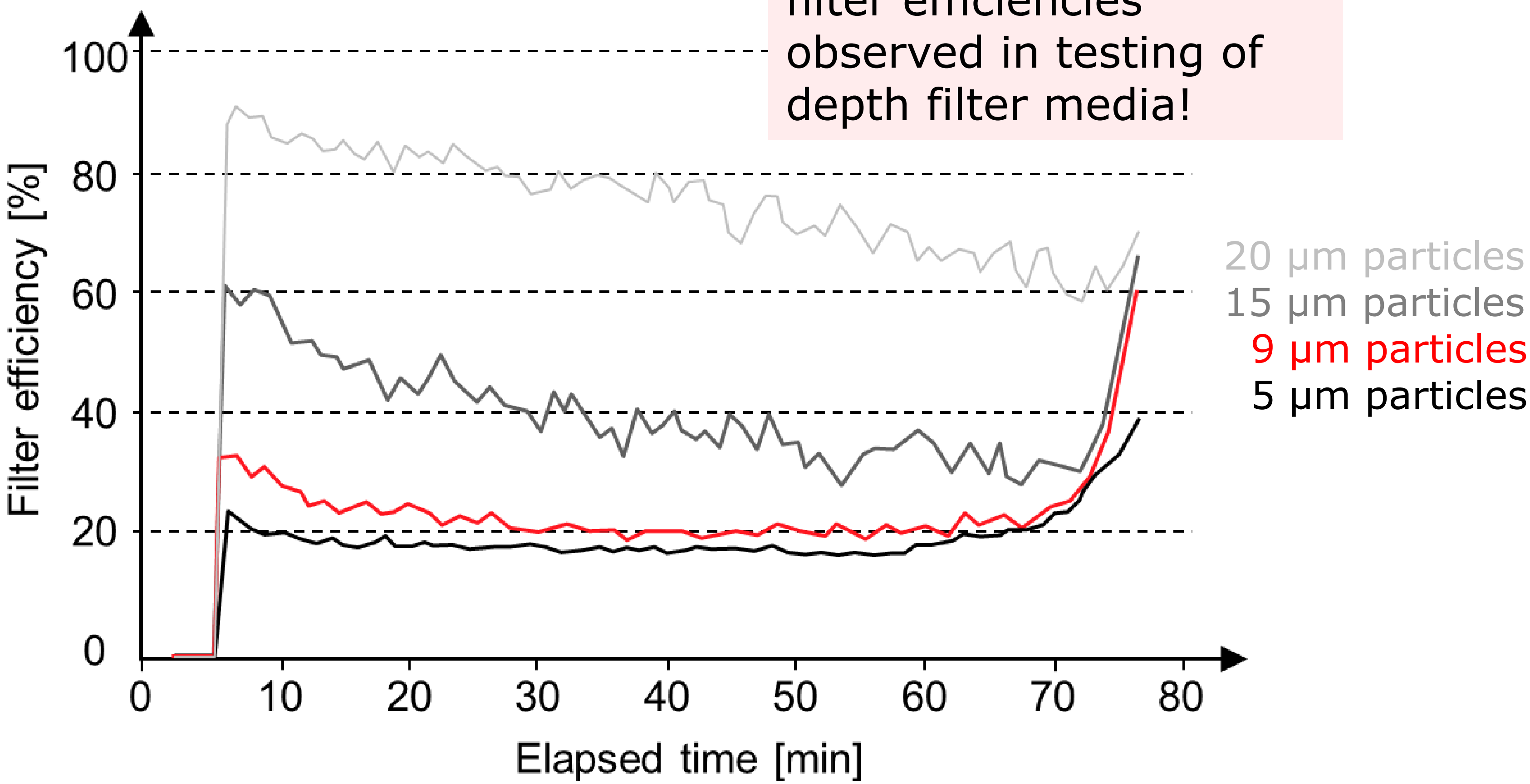
Filter Capacity and Life Time





The Multipass Test (ISO 4548)

Decreasing fractional filter efficiencies observed in testing of depth filter media!



Improvements to FilterDict ...

- Global time concept: particles can continue to the next batch
  - allows lingering particles
  - needed for re-entrainment
- Enabled re-entrainment
  - Compare surface forces from adhesion and shear stress
- Previous particle tracking
  - flow solver uses staggered grid but writes cell-centered result file
  - particle tracking uses cell-centered file
=> accuracy lost (especially at no-slip boundary)
- New particle tracking (2013)
  - flow solver uses staggered grid and writes staggered grid result file
  - particle tracking uses staggered grid
- Introduction of ghost particles to decrease error bars for efficiency

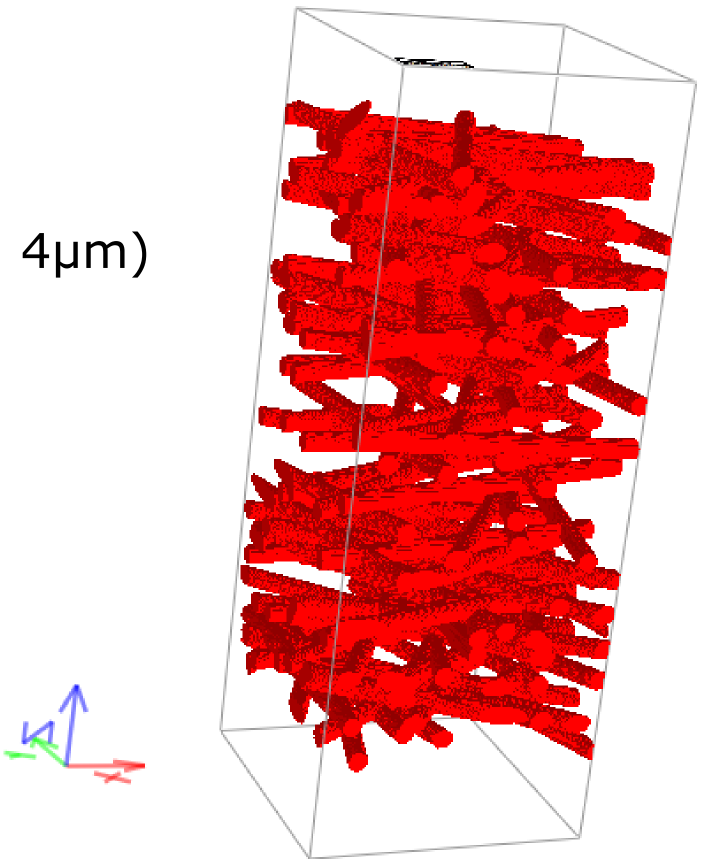
Effect of Higher Accuracy: MPPS Simulation Example

Structure:

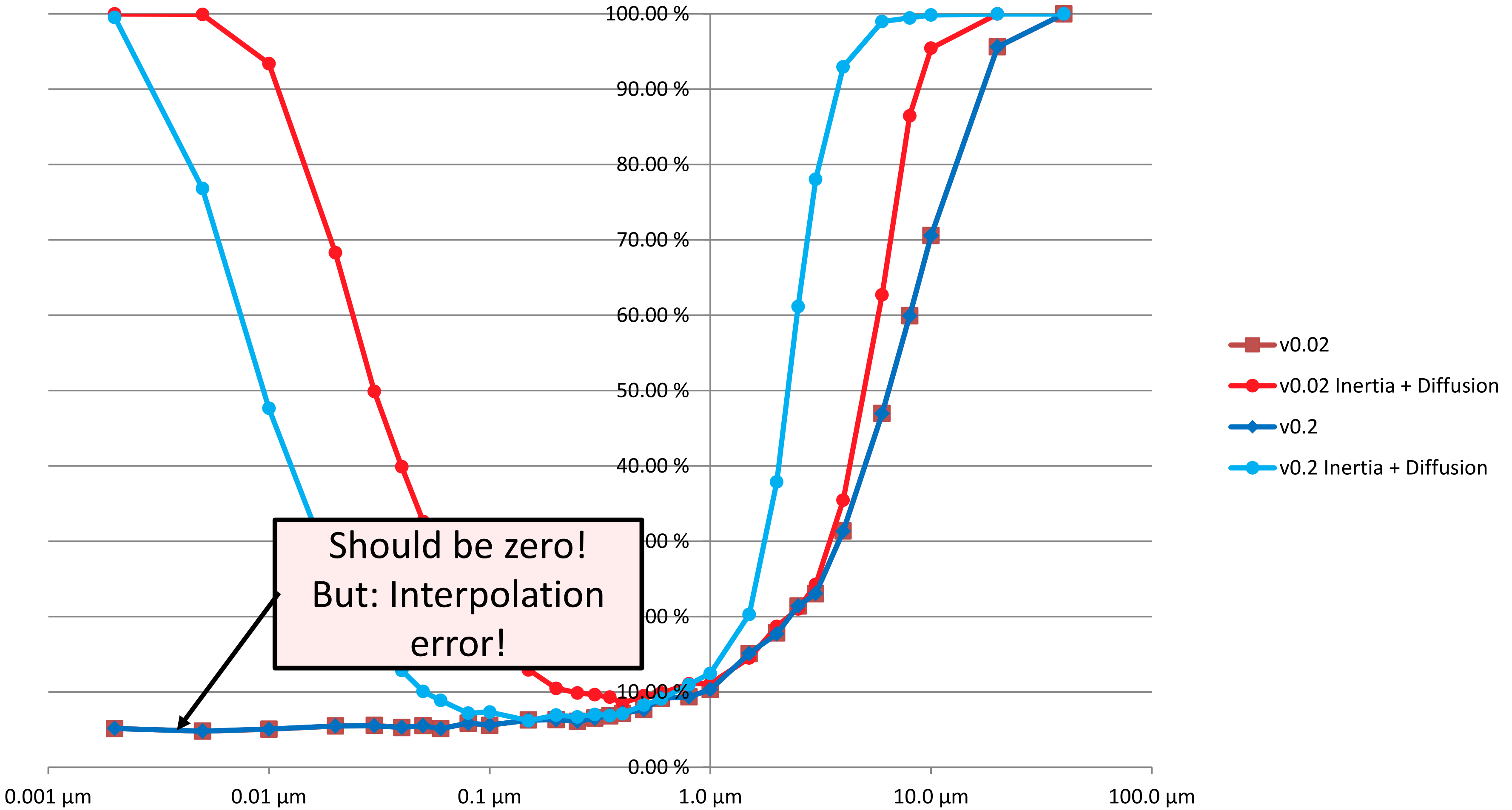
- Fibers with diameter 20 µm
- Different porosities
- Different resolutions (voxel length 1 µm – 4µm)

Simulation:

- Find efficiency for all particle diameters (caught on first touch, air filtration)
- Brownian Motion: on/off
- Inertia: on/off (by particle weight)
- Different flow velocities



Fixed: Porosity 90%, Resolution 2 µm
Vary: Velocity



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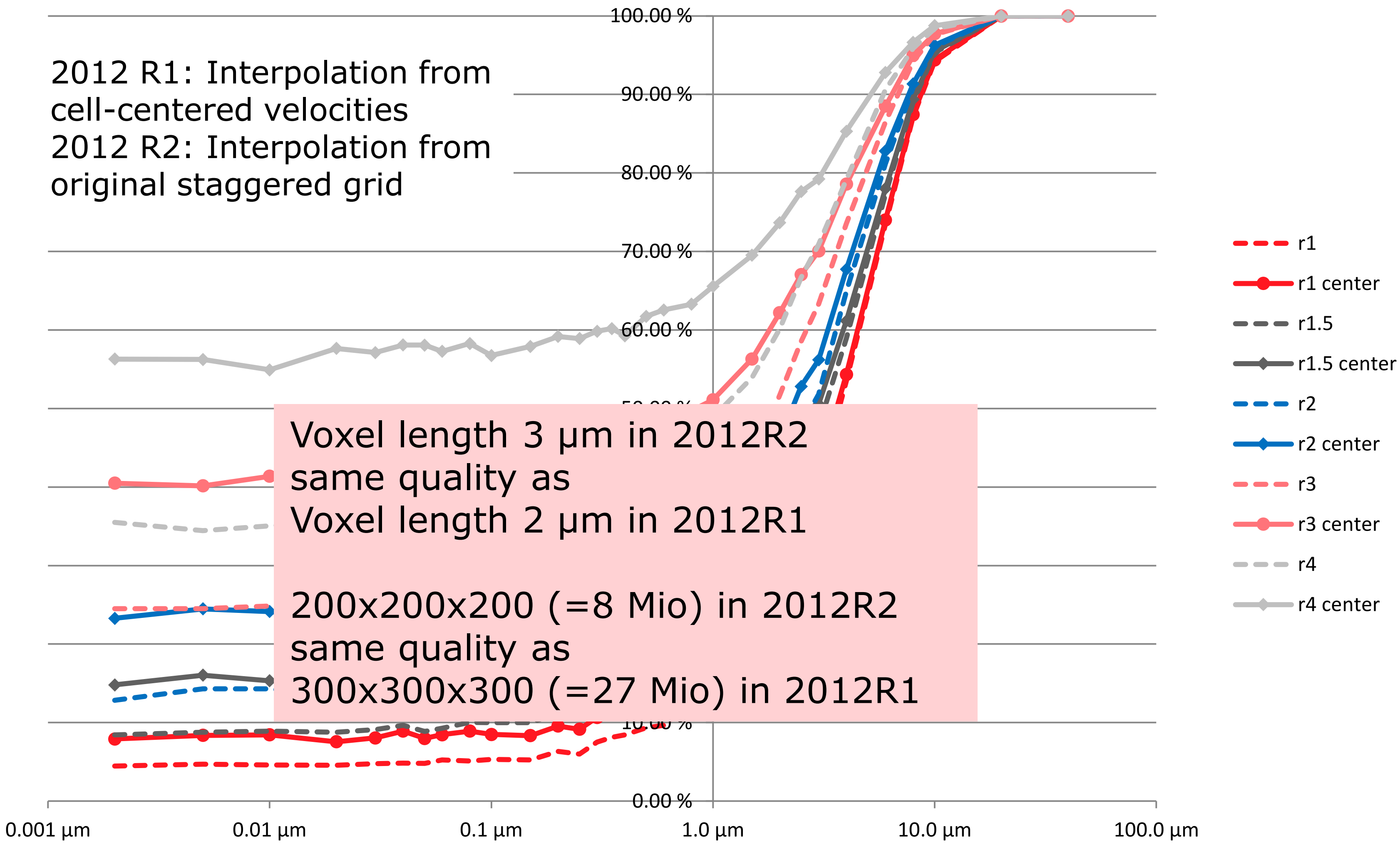
Enhancement of Interpolation in 2012R2

2012 R1: Interpolation from cell-centered velocities
2012 R2: Interpolation from original staggered grid



Voxel length 3 µm in 2012R2
same quality as
Voxel length 2 µm in 2012R1

200x200x200 (=8 Mio) in 2012R2
same quality as
300x300x300 (=27 Mio) in 2012R1

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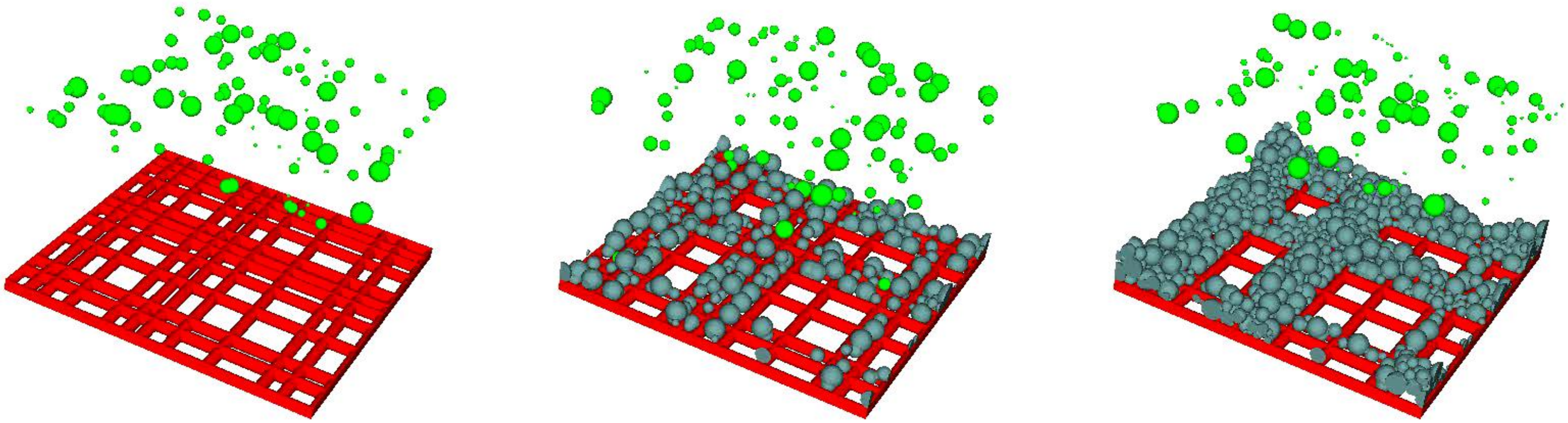
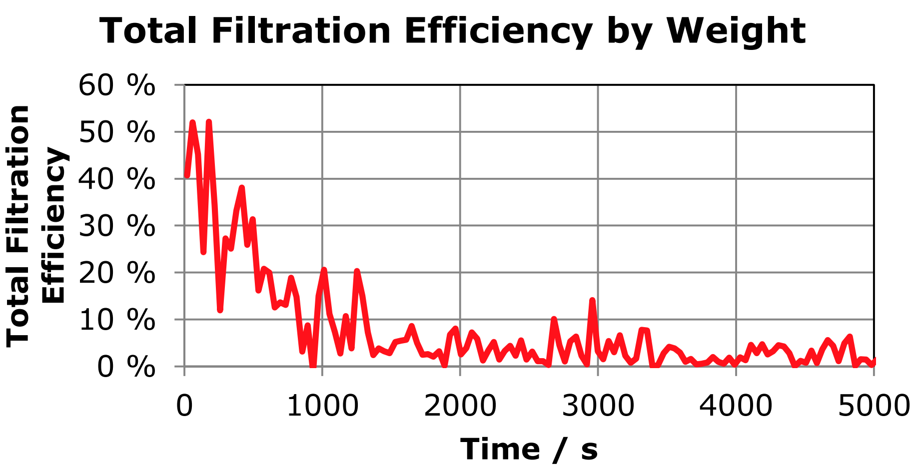
Decreasing Efficiency by Changed Pathways

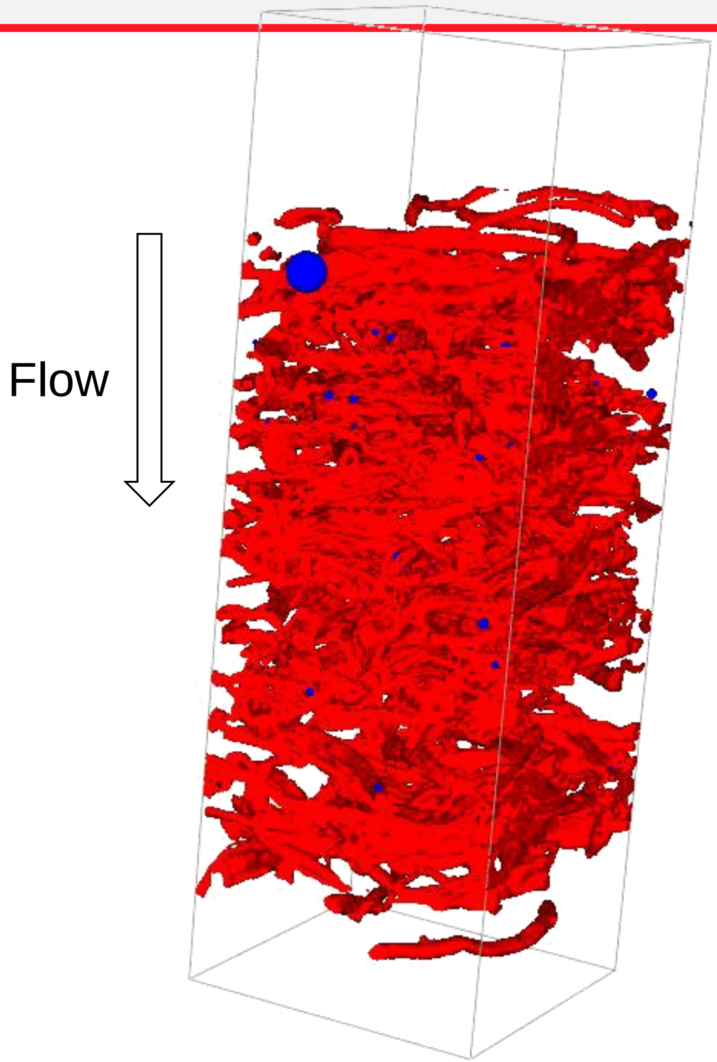




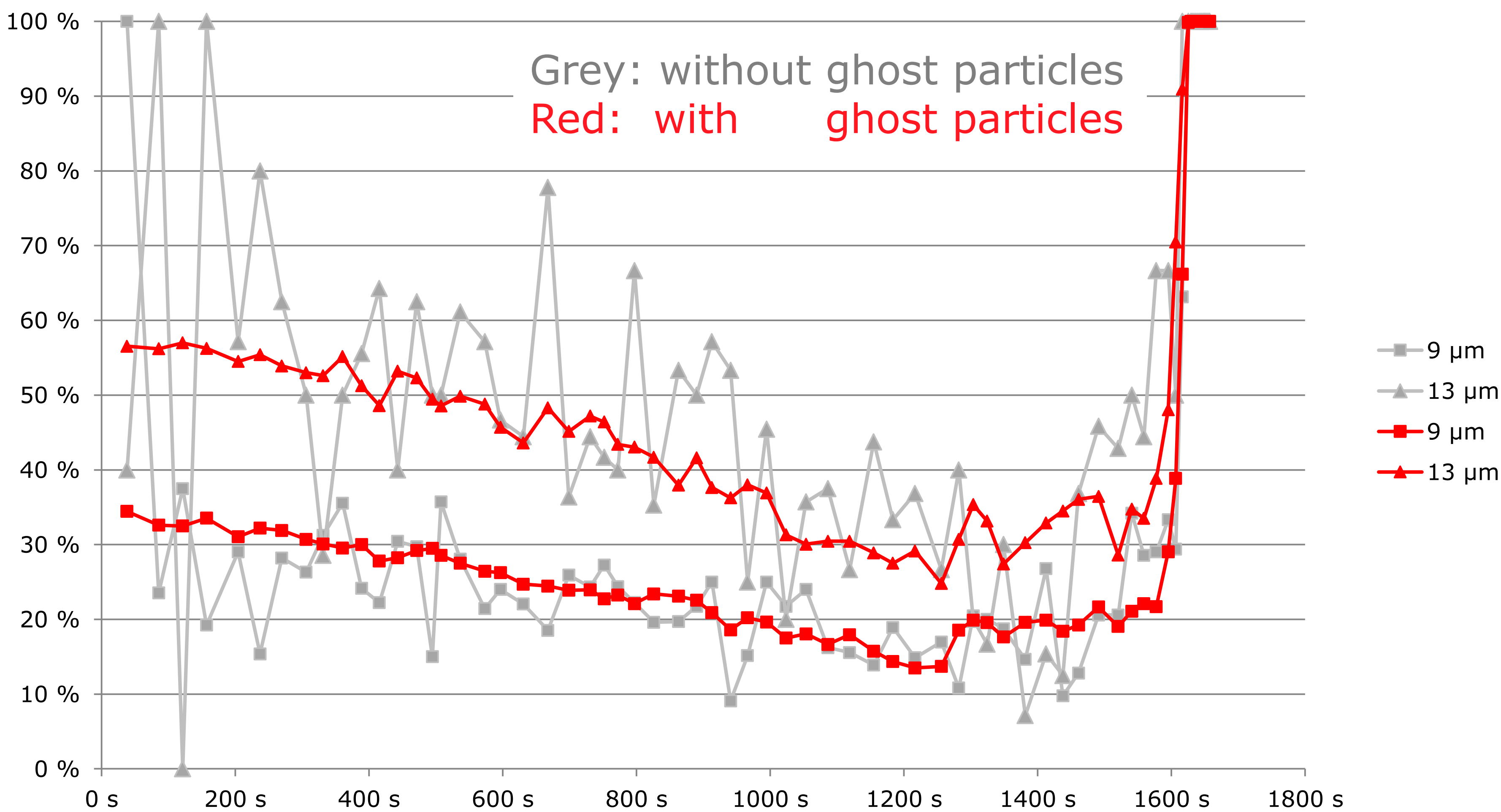
=> Effect can explain decreasing efficiencies!

Clogging simulation on µCT scan

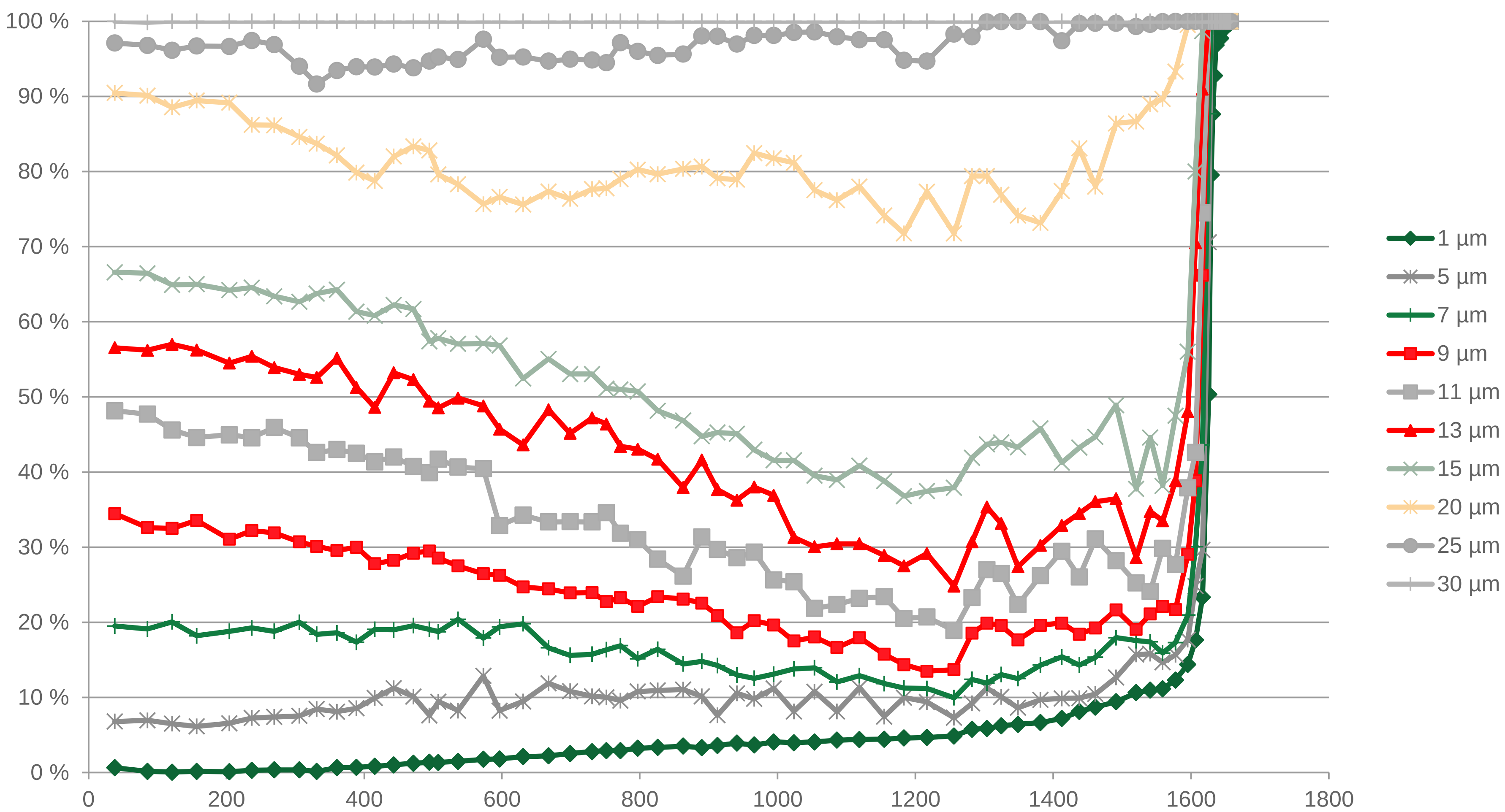
- Cut-out
- Oil filtration
- Particle size distribution from experiment



Simulated filter efficiency enhanced by ghost particles



Enhanced Simulated Fractional Efficiency



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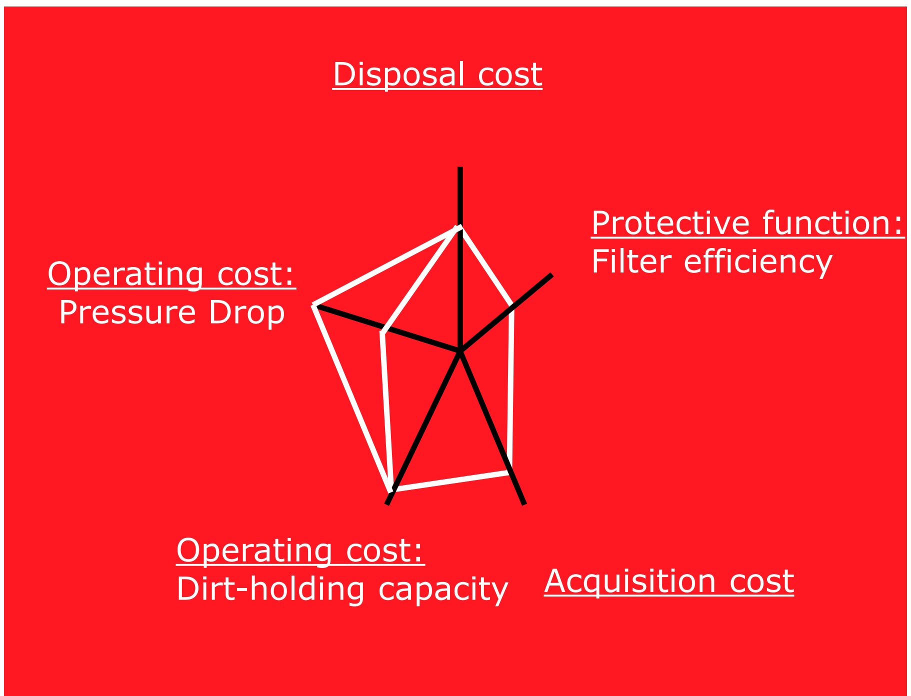
Case Study:
Pressure Drop improvement for a Hydraulic Filter (Patent granted to Argo-Hytos)

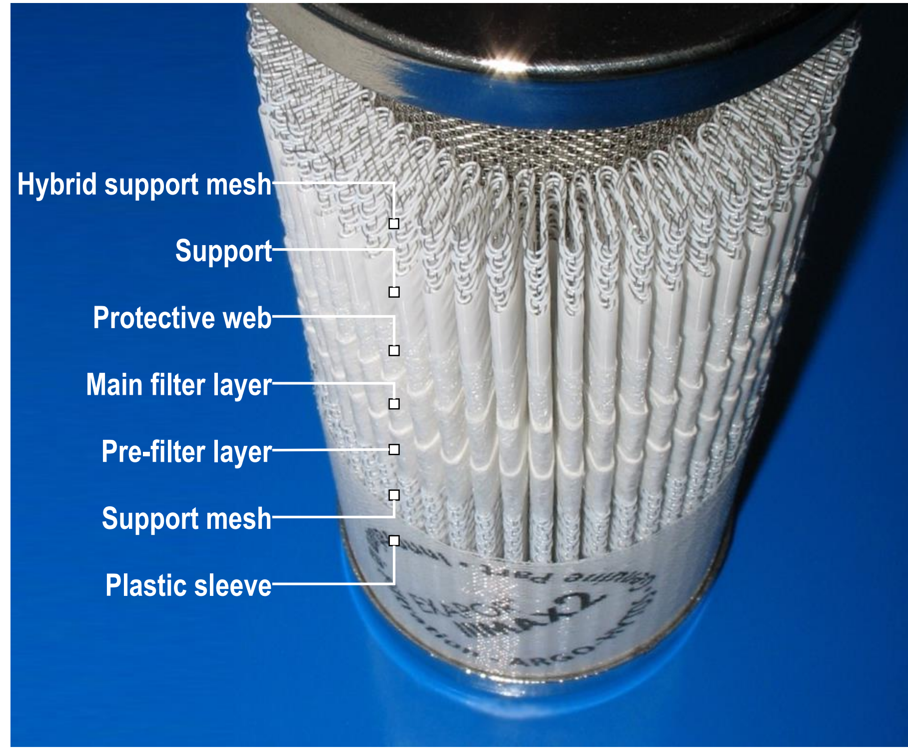
- Oleg Iliev & Andreas Wiegmann
  Fraunhofer ITWM, Kaiserslautern, Germany
- Andreas Schindelin,
  Argo-Hytos GmbH, Kraichgau, Germany

- Originally presented at CVTS Kaiserslautern

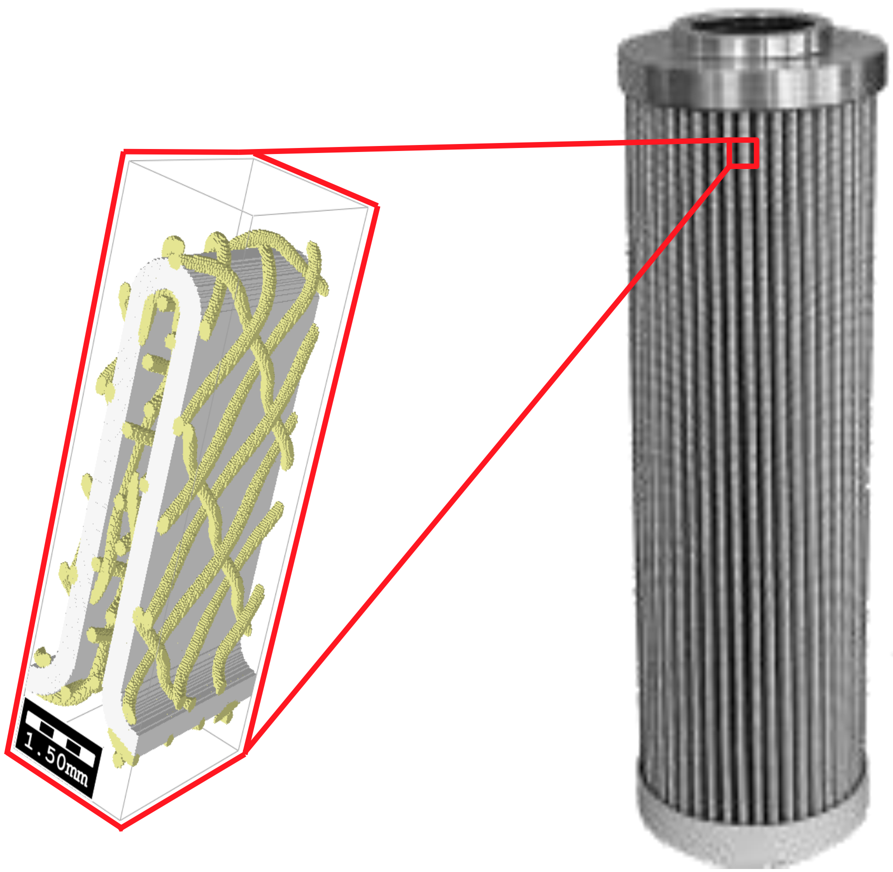
Parameters for a hydraulic filter element

- Oil flows from outside to inside
- Oil exits through perpendicular center region
- Oil passes through layered filter media
- Filter media removes dirt particles from oil

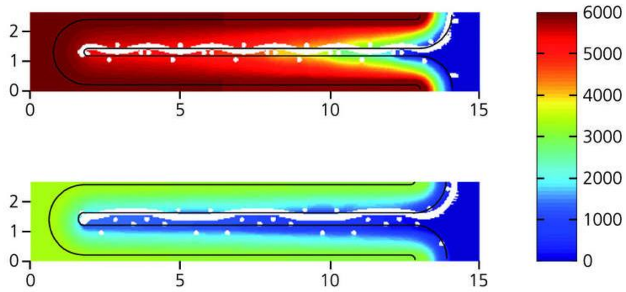




Hydraulic filter with supported pleat



Source: webpage [Argo-Hytos]



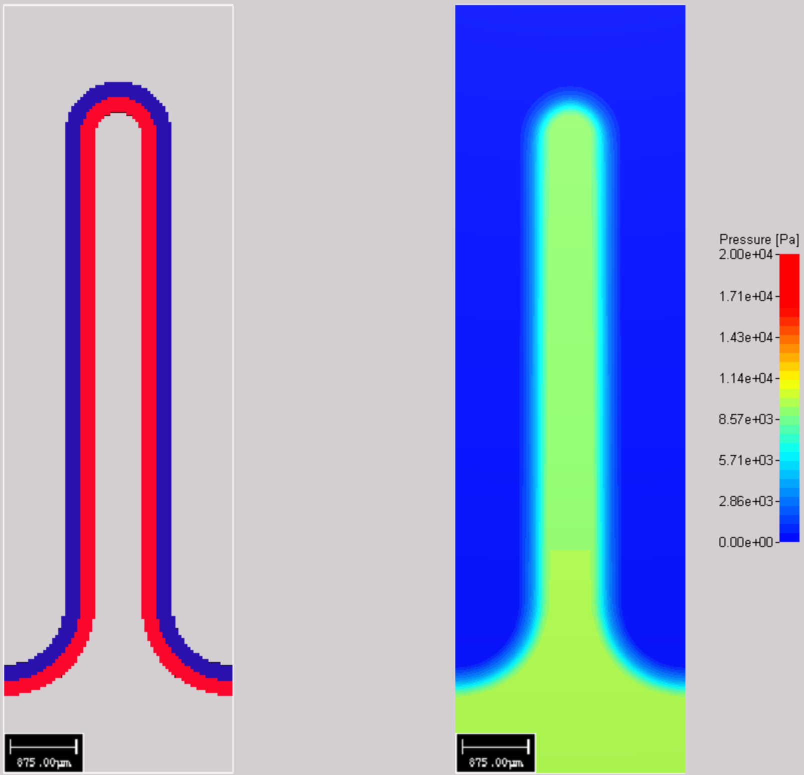
Two effects lead to pressure loss:

1. Across the filter media
2. Along the outflow channels

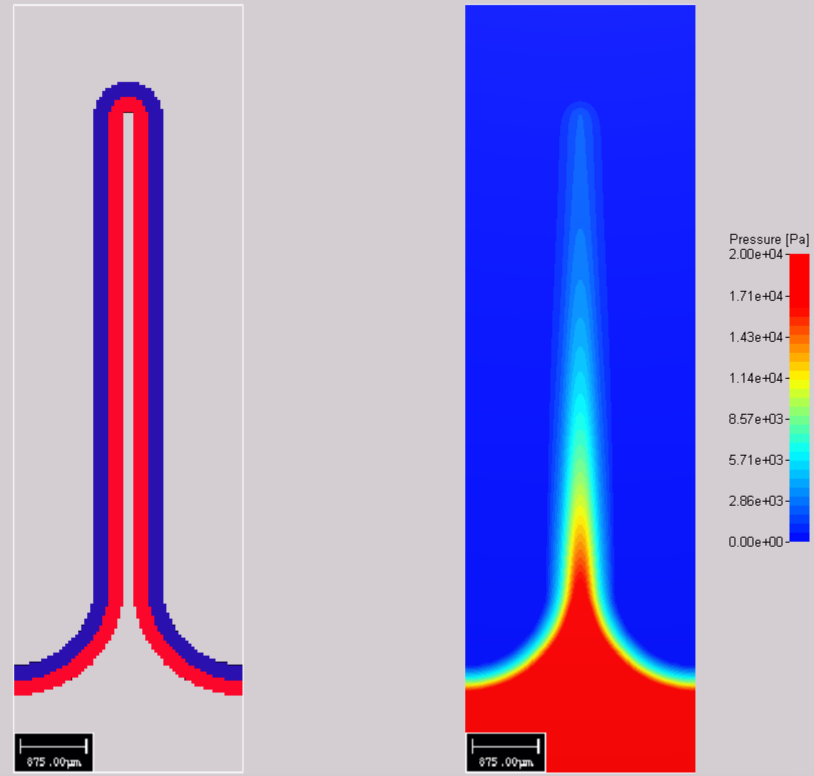
A support mesh prevents the collapse of the outflow channel

Pressure drop from media & capillary

Pressure at 0.01 m/s



Pressure at 0.01 m/s



Wide outflow channel looses 1 bar over filter media

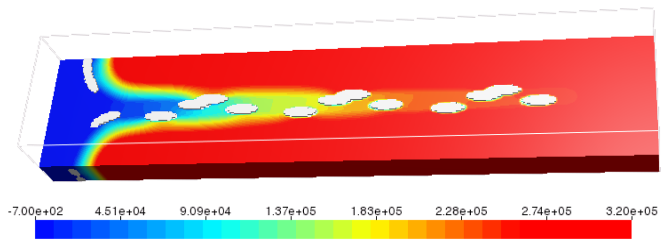
Narrow outflow channel looses 2 bars over filter media and channel

Optimized hydraulic filter

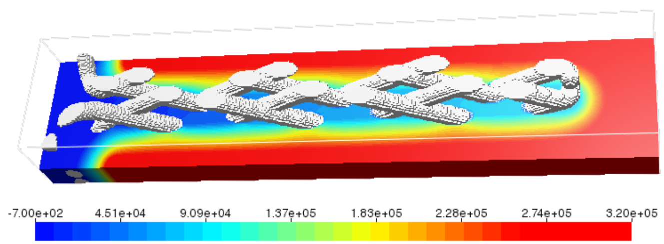
FlowDict

- Same pleat count
- Vary channel width by weave pattern & wire diameter

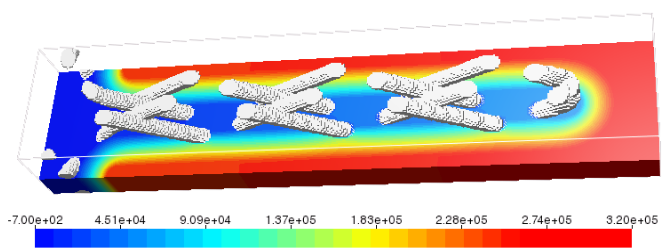
Trying different parameters, the pressure drop could be lowered by more than 35%, by reducing the pressure loss along the outflow channel.



Narrow Channel: 4 bar



Thick Wire: 3.1 bar



Thin Wire: 2.7 bar

Wiegmann, O. Iliev, and A. Schindelin, Computer Aided Engineering of Filter Materials and Pleated Filters, Global Guide of the Filtration and Separation Industry by E. von der Luehe. VDL - Verlag, 2010, pp 191-198.

The optimized filter element …

Innovation in filtration

ARGO-HYTOS sets the standard with the introduction of EXAPOR®MAX 2

Higher machine availability, longer service intervals and lower operating costs. These were the development goals for the new generation of filter elements.

With the introduction of **EXAPOR®MAX 2**, ARGO-HYTOS is opening a new chapter in filtration for hydraulic and lubrication systems.

The structure of the specially developed 3-layer filter material was designed for optimum performance, using glass and polyester fibers of different finenesses combined with an improved hybrid support fabric (patent pending) made of stainless steel and polyester. This sets the standard for:

- **Pressure loss**
- **Dirt holding capacity**
- **Flow fatigue stability**

The plastic sleeve used on the **EXAPOR®MAX 2** for the first time offers the following benefits:

- **Custom label**
- **Protection from damage**
- **Improvement of flow fatigue stability**

For the user, these improvements bring:

- **Extended service intervals**
- **Higher operational reliability**
- **Improved oil cleanliness**
- **Increased performance**
- **Positive element identification**
- **Reduced operating and maintenance costs**

Focus on user benefits

Extended service intervals

Higher dirt holding capacity and improved flow fatigue stability are of particular importance in achieving extended service intervals.

The new performance-oriented structure of the filter material makes a substantial contribution to improving dirt holding capacity, reducing pressure losses and improving the differential pressure stability. The improved hybrid support fabric (patent pending) dissipates electrostatic charge completely, gives the best possible flexural strength while reducing pressure losses. The plastic sleeve shrunk onto the filter bellows ensures that it tightly fits the edges of the hole, which has a positive effect on flow fatigue stability. These improvements make a substantial contribution to increasing the life of the filter elements.

Higher operational reliability

When used on existing machinery with fixed service intervals, **EXAPOR®MAX 2** filter elements bring greater operational reliability, minimizing the risk of sudden machine downtimes as well as reducing downtime caused by time-consuming and expensive maintenance work.

Improved oil cleanliness

A high degree of oil cleanliness has a positive effect on both the life of components and that of the hydraulic medium itself. To meet rising standards, in the new generation of filter elements the filter fineness has been improved to 10 µm(c) compared with 12 µm(c) previously. The **EXAPOR®MAX 2** filter elements are available in filter finenesses of 5 µm(c), 10 µm(c) and 16 µm(c).

Increased performance

The factors that influence pressure loss could be worked out with the aid of calculations and flow simulations, and the structure of the filter material optimized accordingly. The result is a reduction in pressure losses in the pleat of up to 50% and up to 40 % in the filter element. Conversely, this means that at a constant pressure loss the **EXAPOR®MAX 2** filter elements can achieve a flow rate that is up to 65 % higher. The substantial reduction in pressure losses allied to an improved dirt holding capacity leads to an increase in power density, so that, depending on the application, smaller filters could be used.

Positive identification of elements

The plastic sleeve used on the **EXAPOR®MAX 2** filter elements can be printed as required. This substantially improves positive identification and is an important feature for building up and securing a strategic spare part business.

Reduced operating and maintenance costs

These innovations work together to reduce operating and maintenance costs and bring about an improvement in the productivity and economy of machinery and plant.

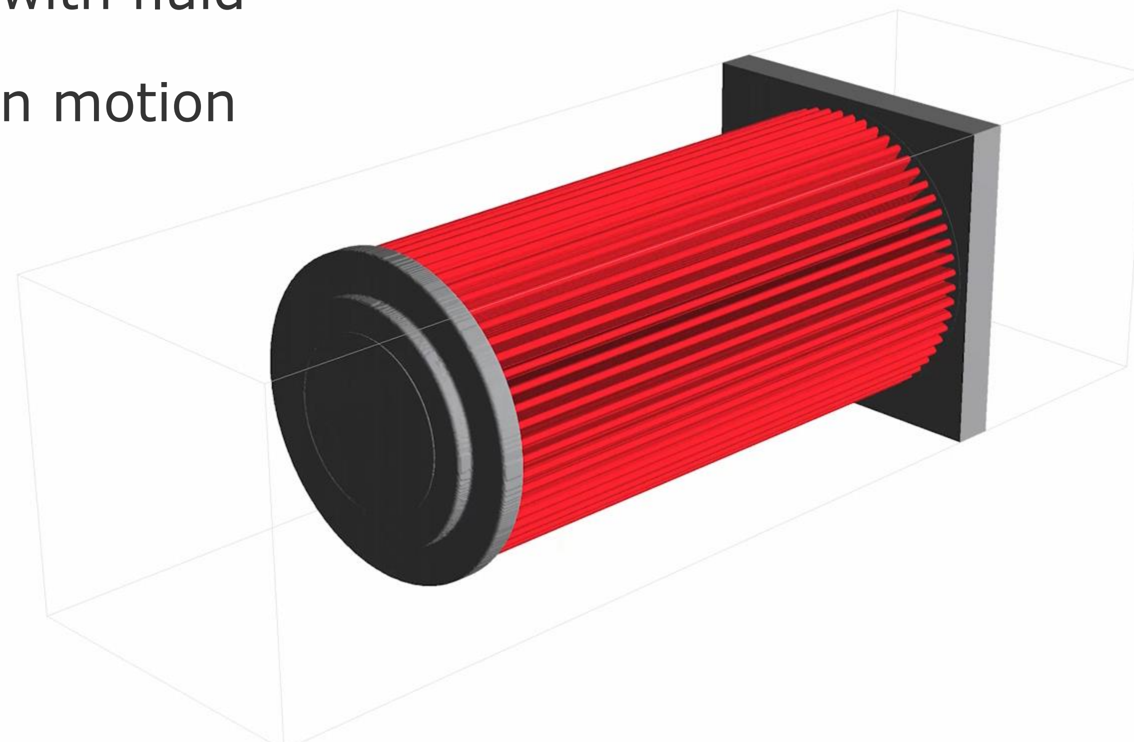
A new design for hydraulic filter lowers the pressure drop by 40-50 %

Patent granted to Argo-Hytos in 2009

2. Track Particles

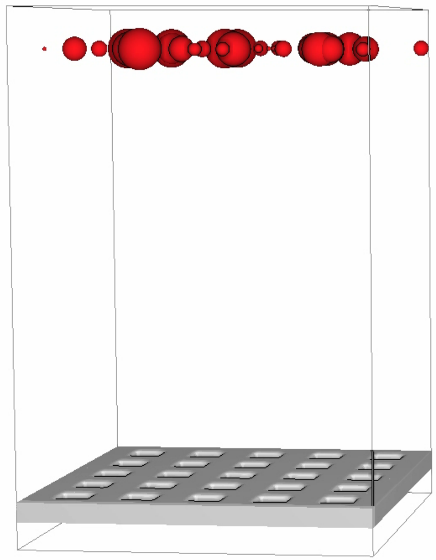
Movement of particles in fluid:

- Friction with fluid
- Brownian motion



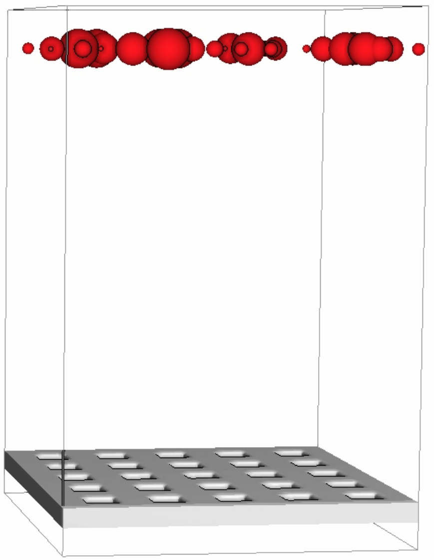
Particles enlarged for visualization

Caught on first touch (air filtration) & sieving collision model (oil filtration)



Caught on first touch

Filter cake with lower density & higher permeability, “dendrites”



Sieving

Filter cake with higher density & lower permeability, “dense packing”

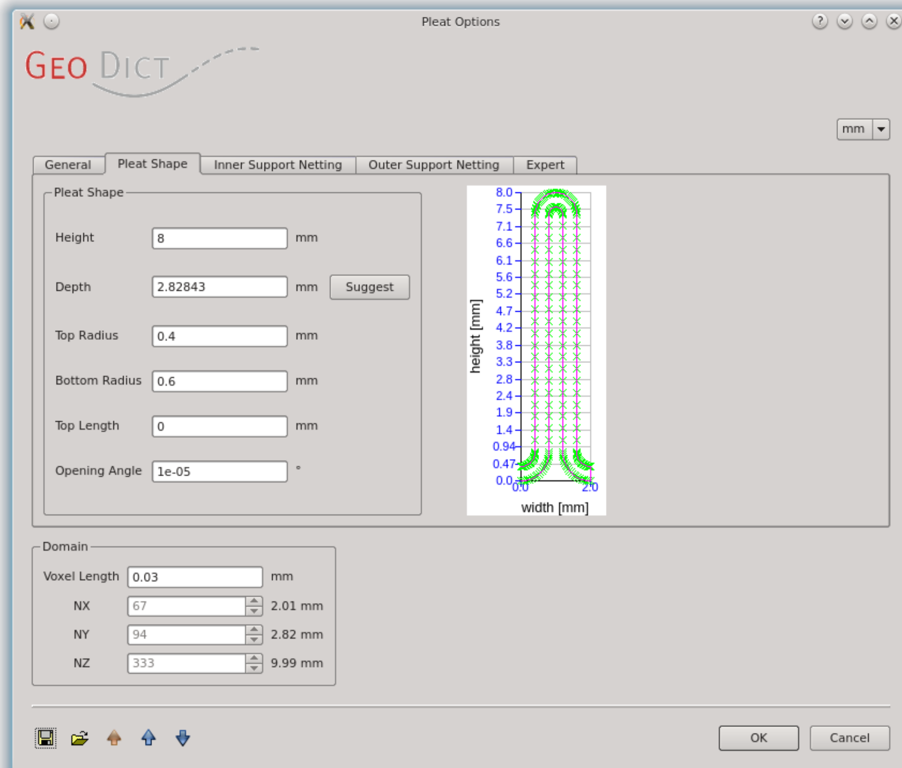
Simulation of pleated air filter (for use in nuclear power plants)

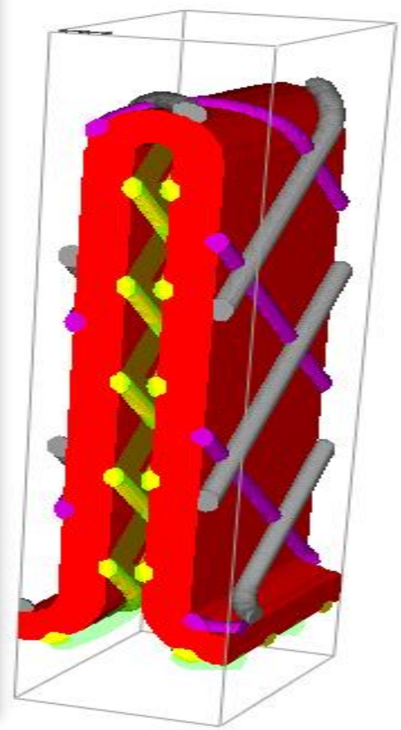
- Jürgen Becker, Liping Cheng, Andreas Wiegmann
  Math2Market GmbH, Kaiserslautern, Germany
- Nathalie Bardin-Monnier, Pierre-Colin Gervais
  Nancy University, France

- Originally presented at Filtech

Pleat simulation

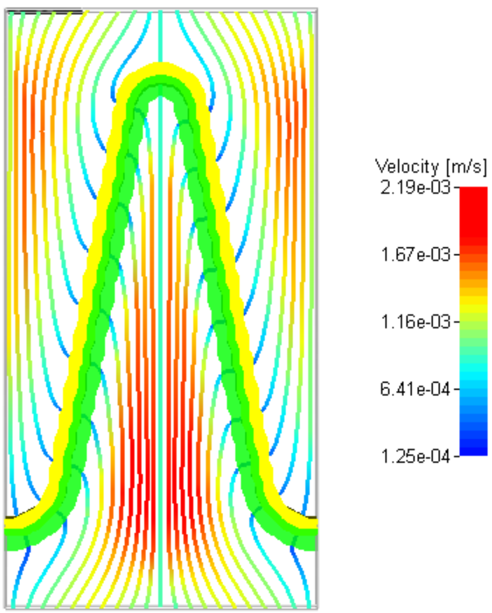
- Pleat generator accounts for
  - Height
  - Width
  - Inner support
  - Outer support
  - Layered media
  - Angled pleats
  - etc



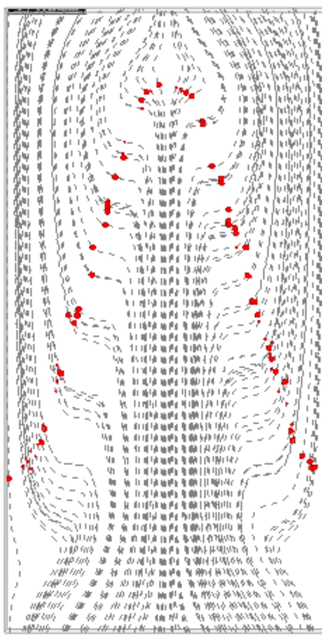


Andreas Wiegmann
AFS 2017, Louisville
11 April 2017

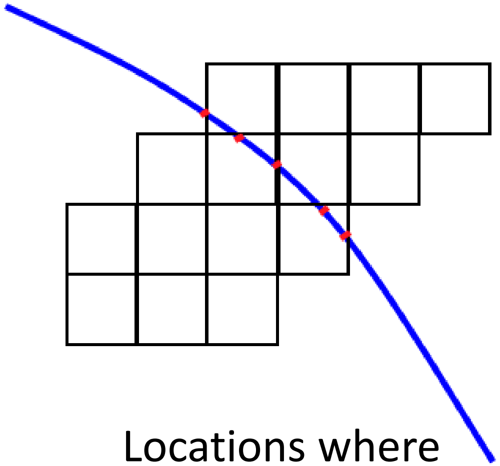
Pleat scale simulation



First, compute the flow in the pleat



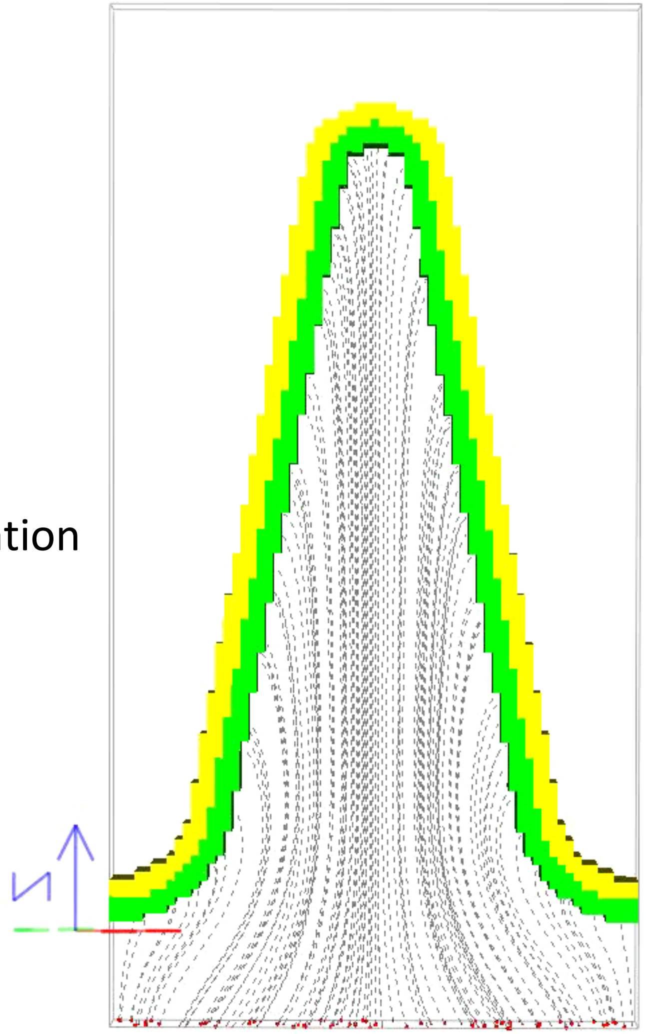
Then, track the particles and find the trajectories following the flow field without obstacles.

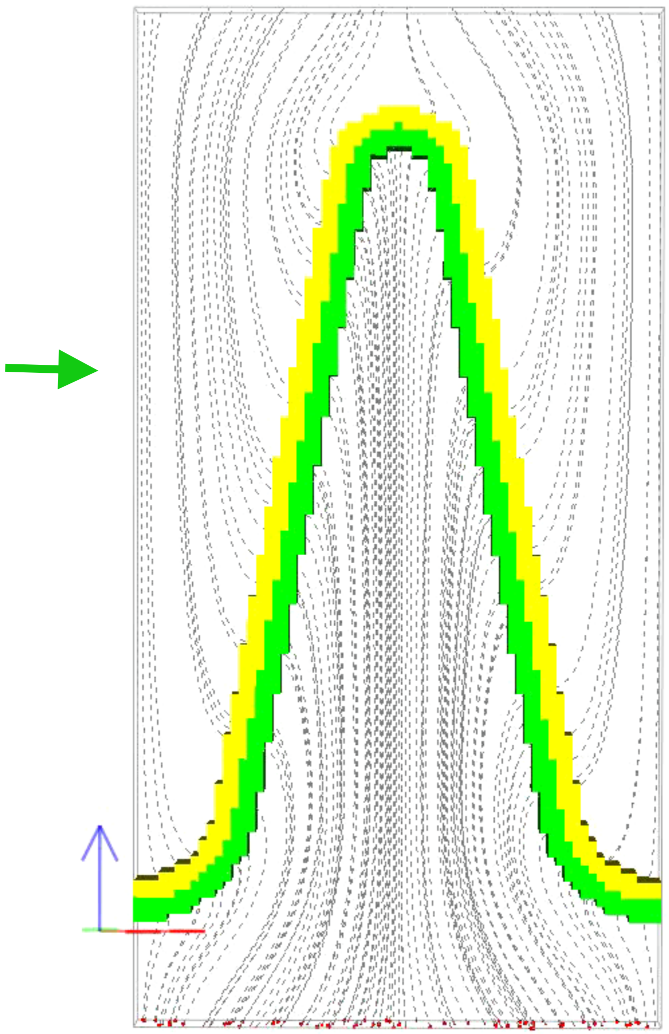


Locations where particles cross the media are found and the probability of particles being captured in the media is determined.

Simulate cake or depth filtration

Cake filtration

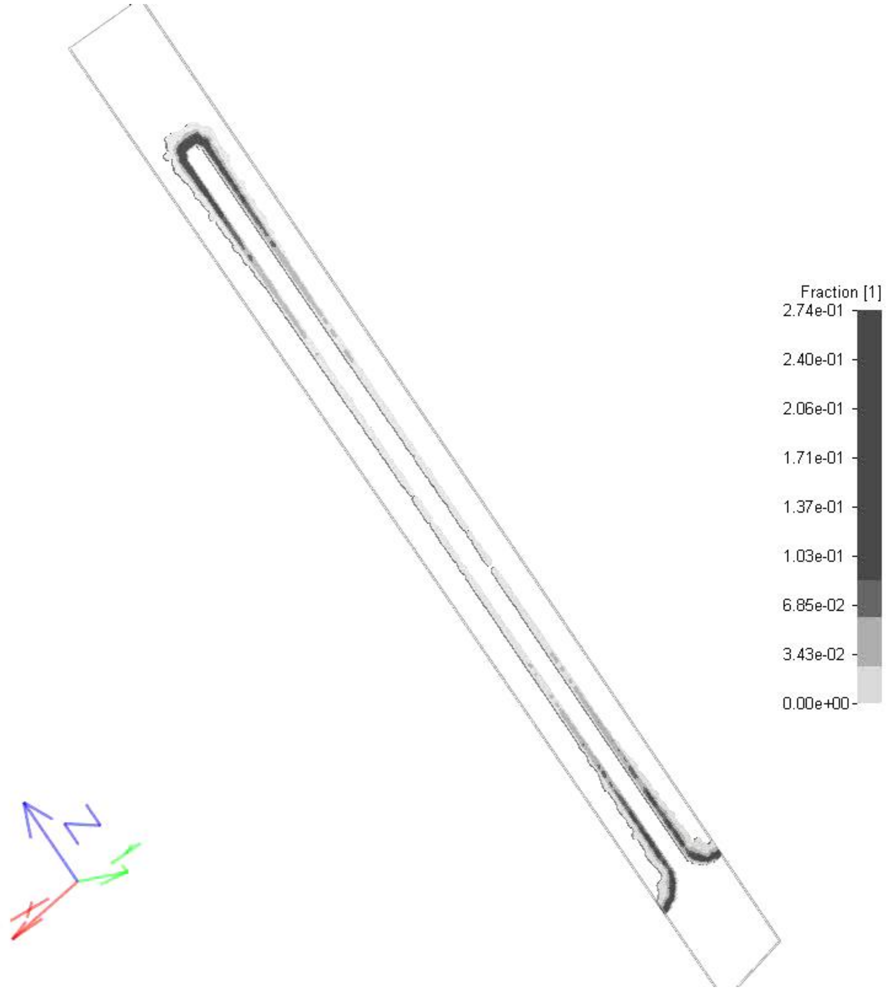


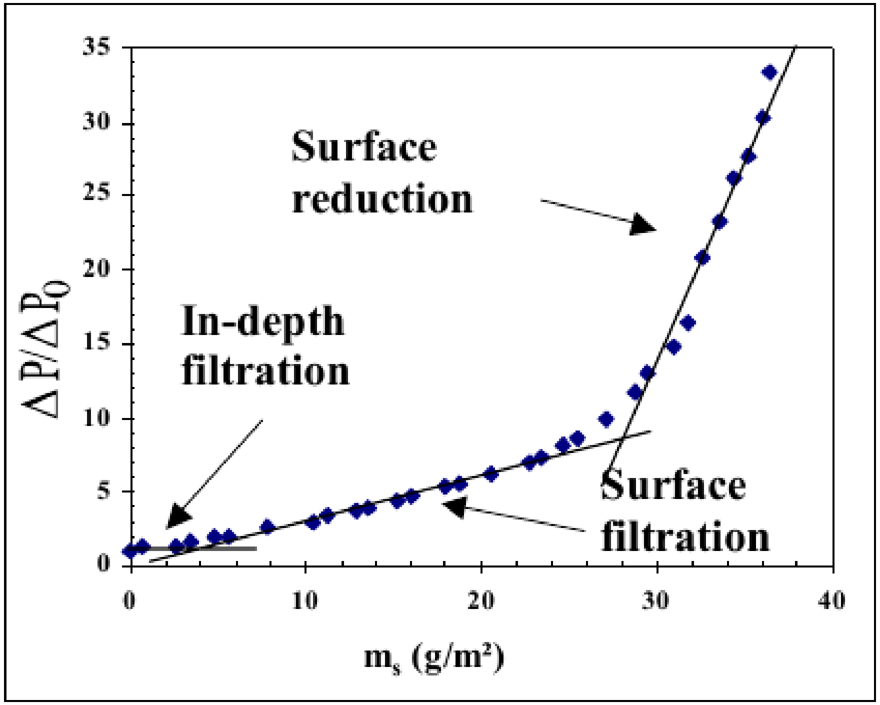


Depth filtration

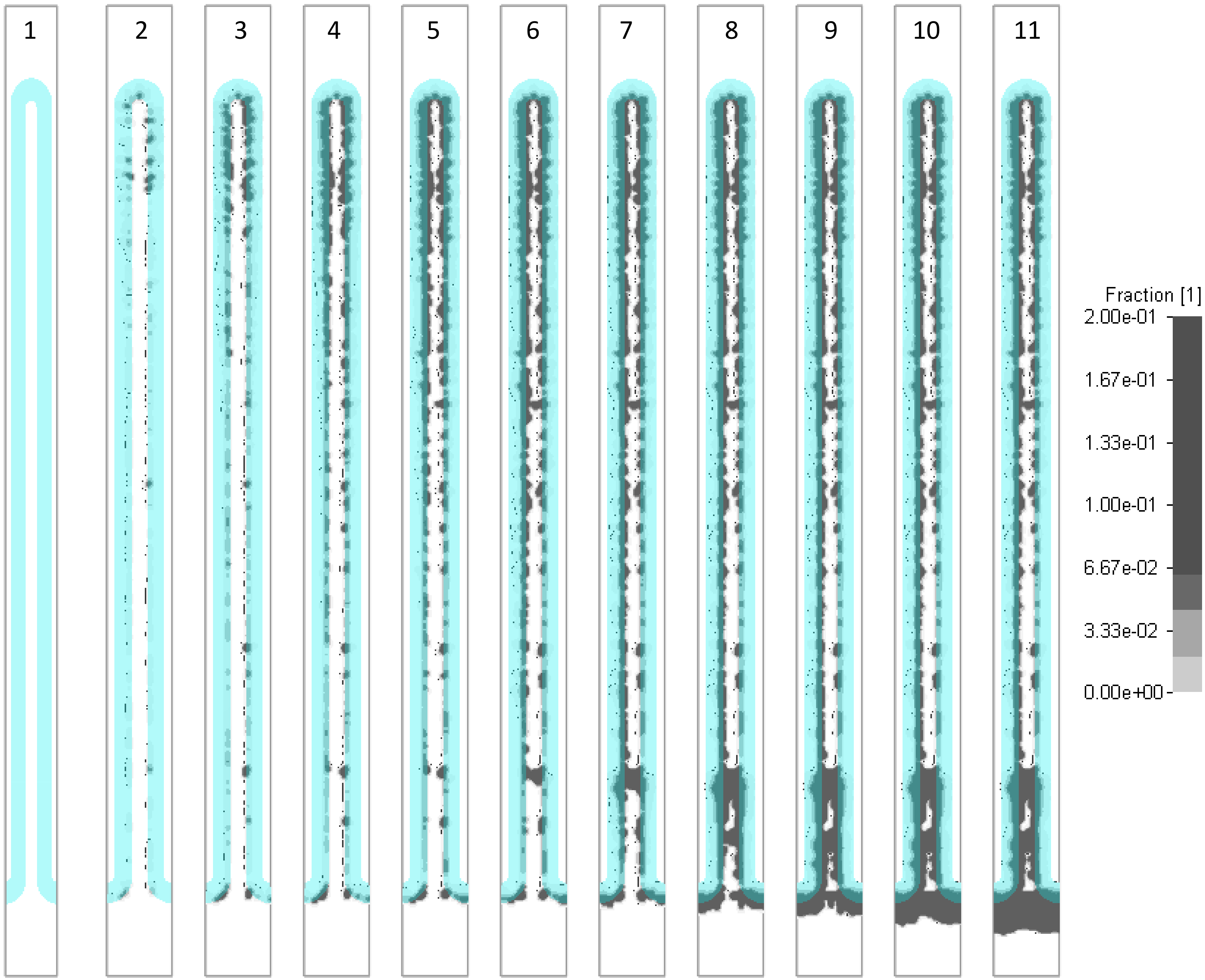
Andreas Wiegmann
AFS 2017, Louisville
11 April 2017

Compare with experimental data





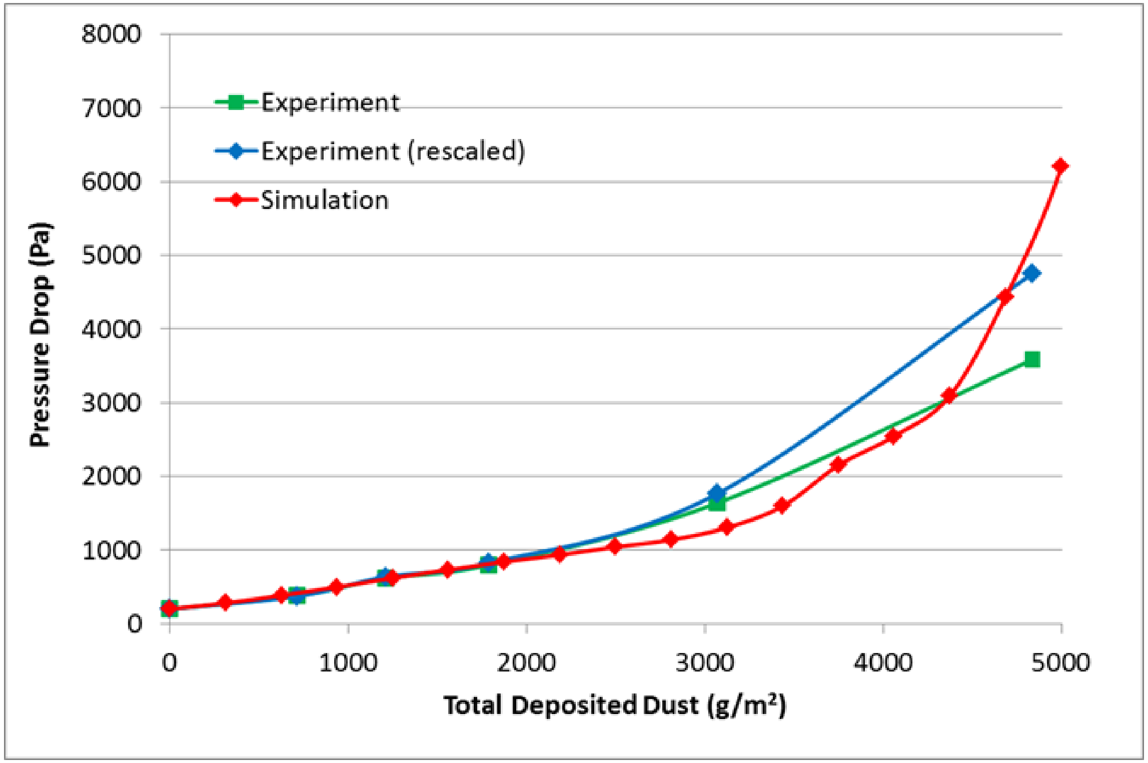
Andreas Wiegmann
AFS 2017, Louisville
11 April 2017



The particle deposition with time

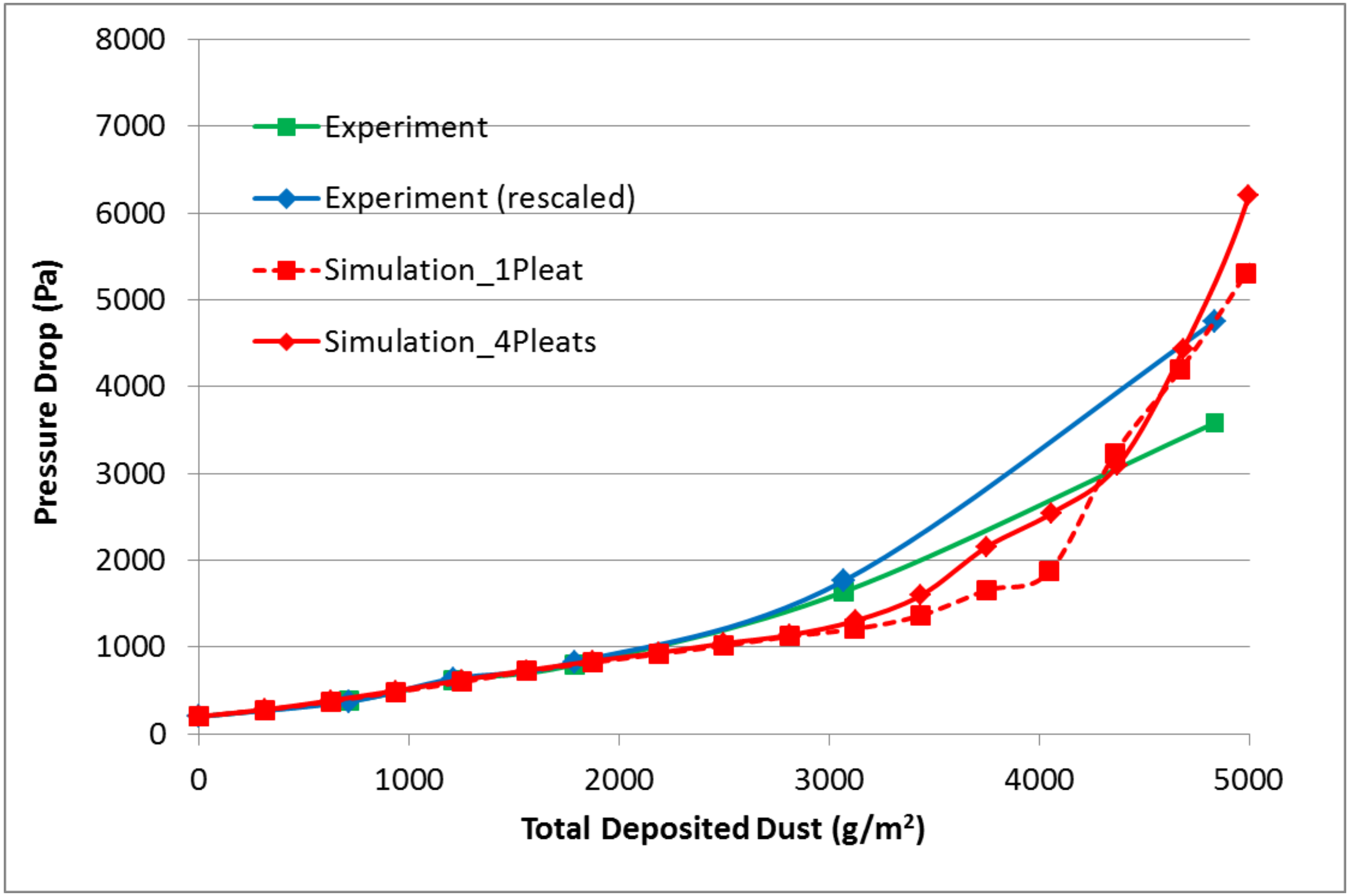
Agreement with experimental data

- Pressure drop vs. load of a pleated filter
- Rescale to constant flow rate, what the pump was asked to do but did not do
- Simulation results compared with experimental measurements (rescaling done w.r.t. fluctuations in the volumetric flow rate)



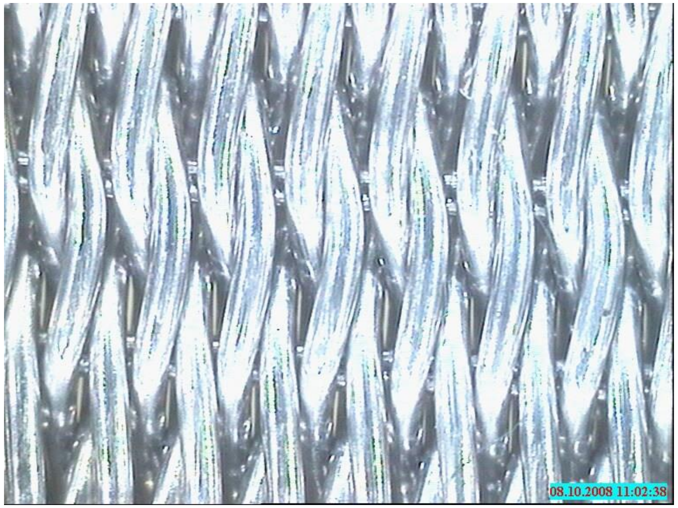
*Pierre-Colin Gervais, Experimental and numerical study of clogging of pleated filters. PhD thesis, CNRS, LRGP, UMR 7274, Nancy, F-54000, France, 2013.

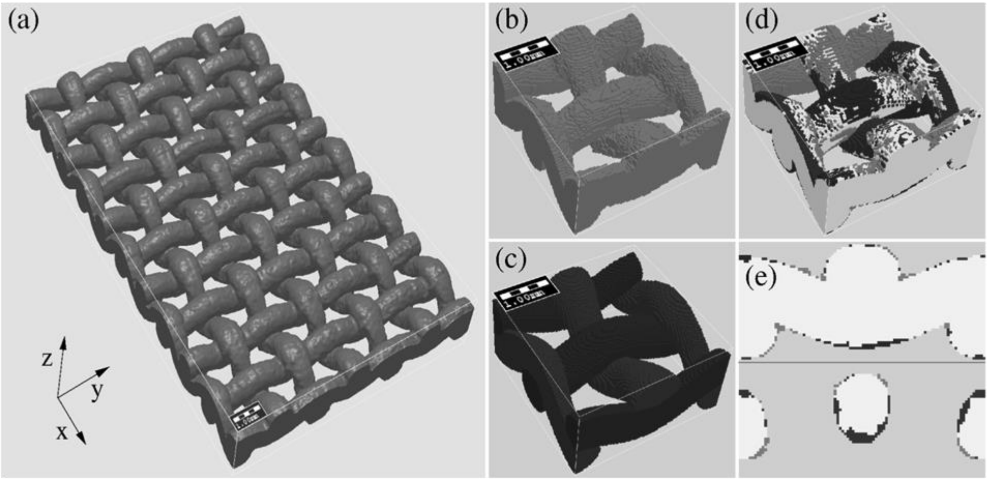
Agreement with experimental data



Metal Wire Mesh

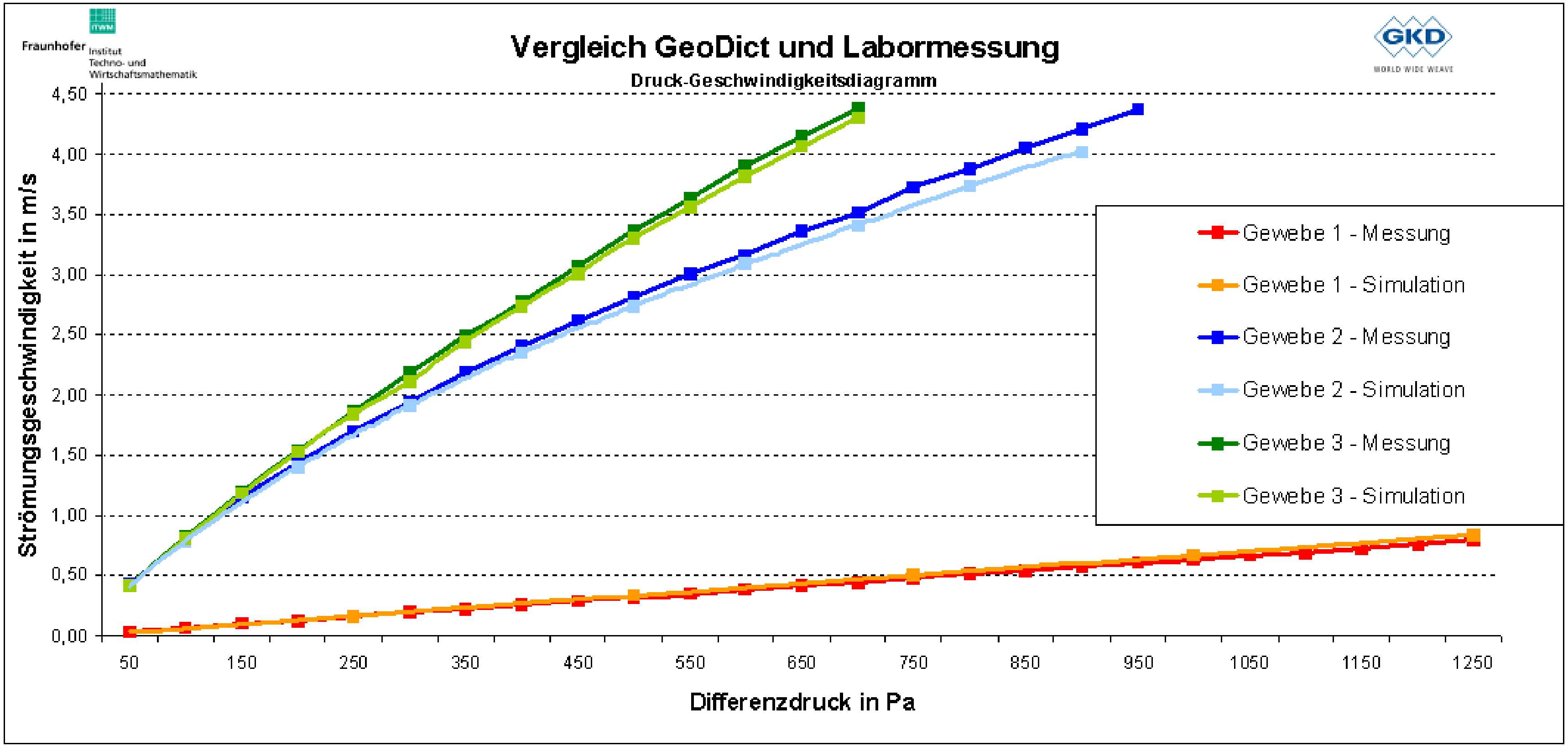
Reconstruction of Woven





E. Glatt, S. Rief, A. Wiegmann, M. Knefel and E. Wegenke, *Structure and pressure drop of real and virtual metal wire meshes*, Bericht des Fraunhofer ITWM, Nr. 157, 2009.

Measured vs Simulated pressure drop for GKD meshes

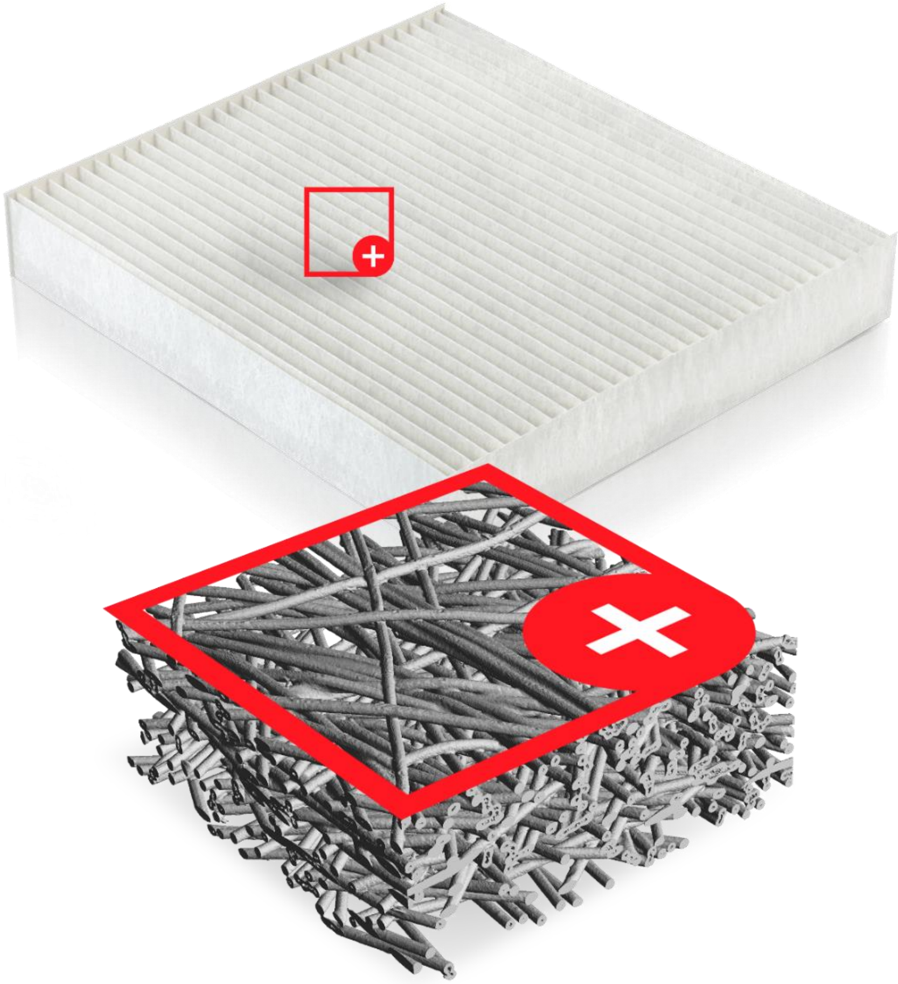


E. Glatt, S. Rief, A. Wiegmann, M. Knefel and E. Wegenke, *Structure and pressure drop of real and virtual metal wire meshes*, Bericht des Fraunhofer ITWM, Nr. 157, 2009.

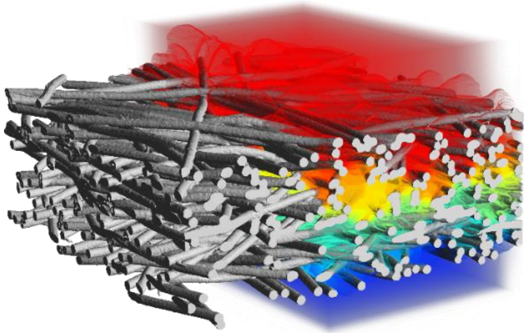
Deviation of simulation and experiment independently confirmed to lie within 3% over all differential pressures by A. Mantler and M. Theiß of Haver & Boecker, 2017.

Case Study: Cabin Air Filter

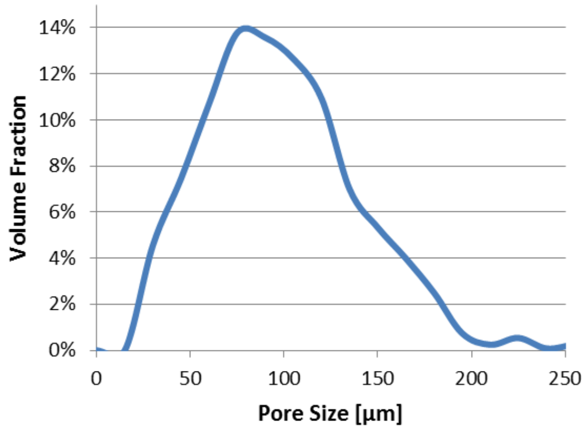
µCT-scan of cabin air filter sample



- Flow and pressure drop

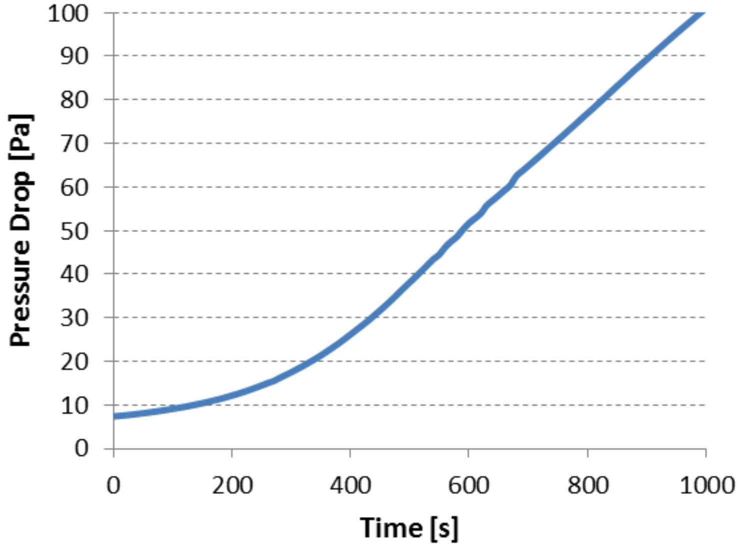


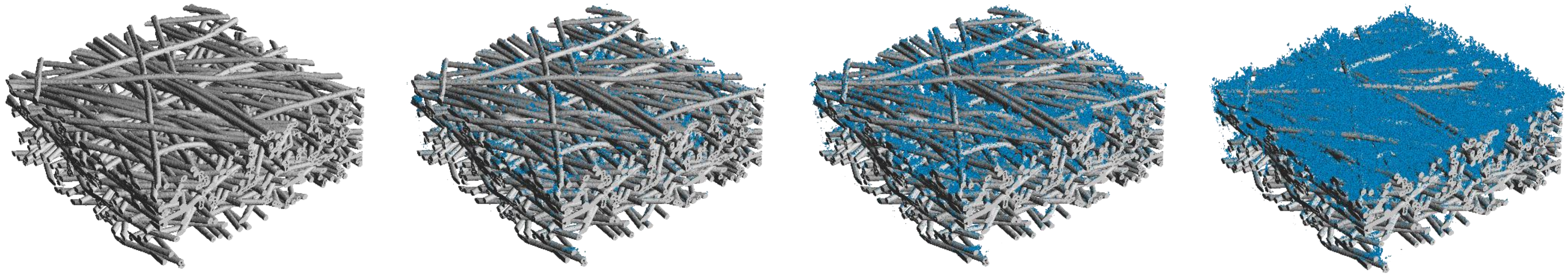
- Pore Size Distribution



Filter Life Time simulation

Initial pressure drop	7 Pa
Pressure drop after 1000s	101 Pa
Total deposited dust after 1000s	93 g/m²
Total filter efficiency	93% (weight)





Improved ceramic for soot filtration (patent granted to Fraunhofer IKTS and Fraunhofer ITWM)

- Liping Cheng & Andreas Wiegmann
  Fraunhofer ITWM, Kaiserslautern, Germany
- Jörg Adler, Uwe Petasch & Lars Mammitsch
  Fraunhofer IKTS, Dresden, Germany

- Originally presented at WFC 12, Graz

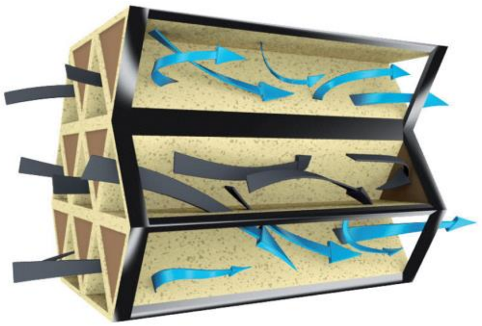
Introduction
Diesel Particulate Filter (DPF)

Goal: design a better DPF using simulations

- lower pressure drop
- higher filter efficiency
- longer life time

key element governing the performance of the DPF:

ceramic filter media



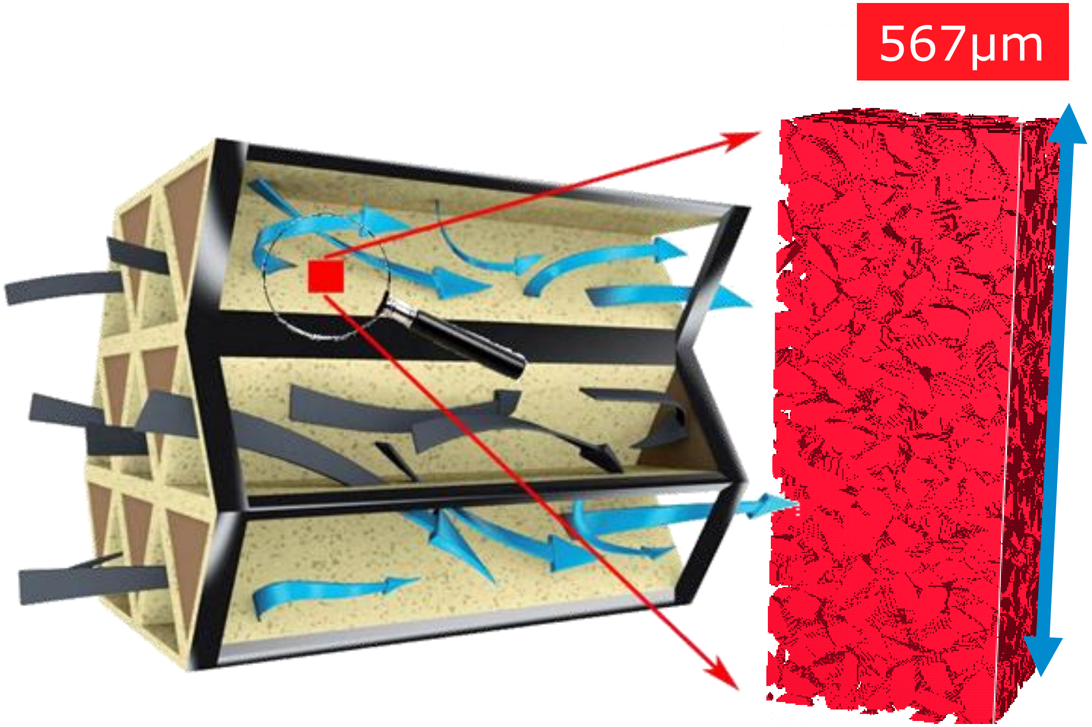
They can be simulated and predicted.

- a multivariate resistivity model is introduced and shown to predict pressure drop measurements

Diesel Particulate Filter Simulations:

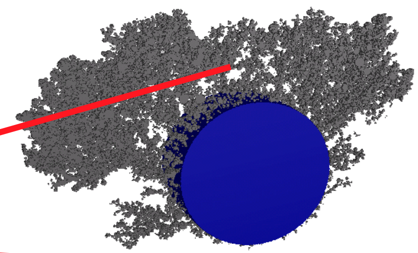
In a Diesel Particulate Filter, soot particles are filtered in the walls of the filter, usually a 50% porosity ceramic

The energy use of the filter is due to pressure loss across the loaded ceramic, as well as along the channels of the DPF. Here, we consider the pressure loss across the wall.



Simulations:	256 x 256 x 750 cells
Grid cells:	0.9 µm x 0.9 µm x 0.9 µm
Soot particle:	25 nm - 600 nm
Wall thickness:	567 µm
Inlet / Flow Channel:	108µm

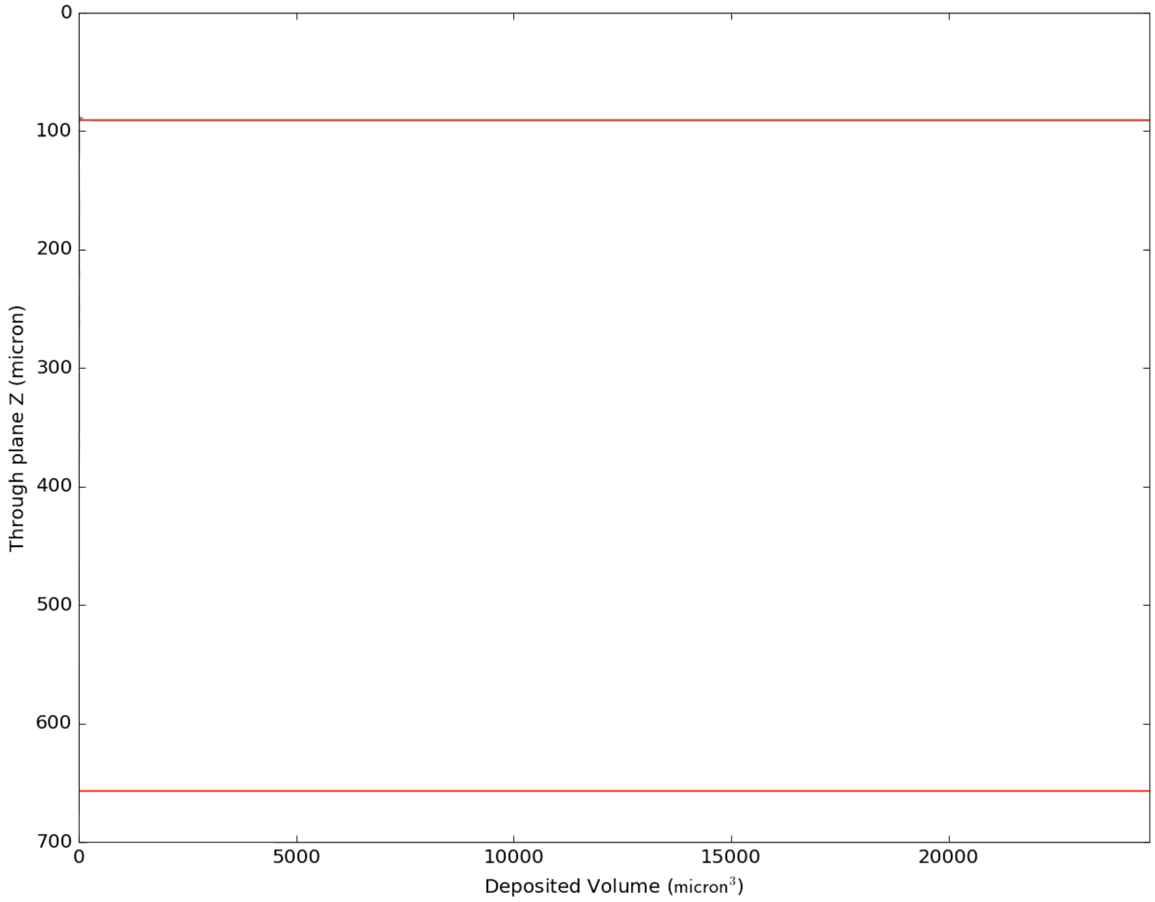
Particle Filtration Tasks: Multi-scale approach



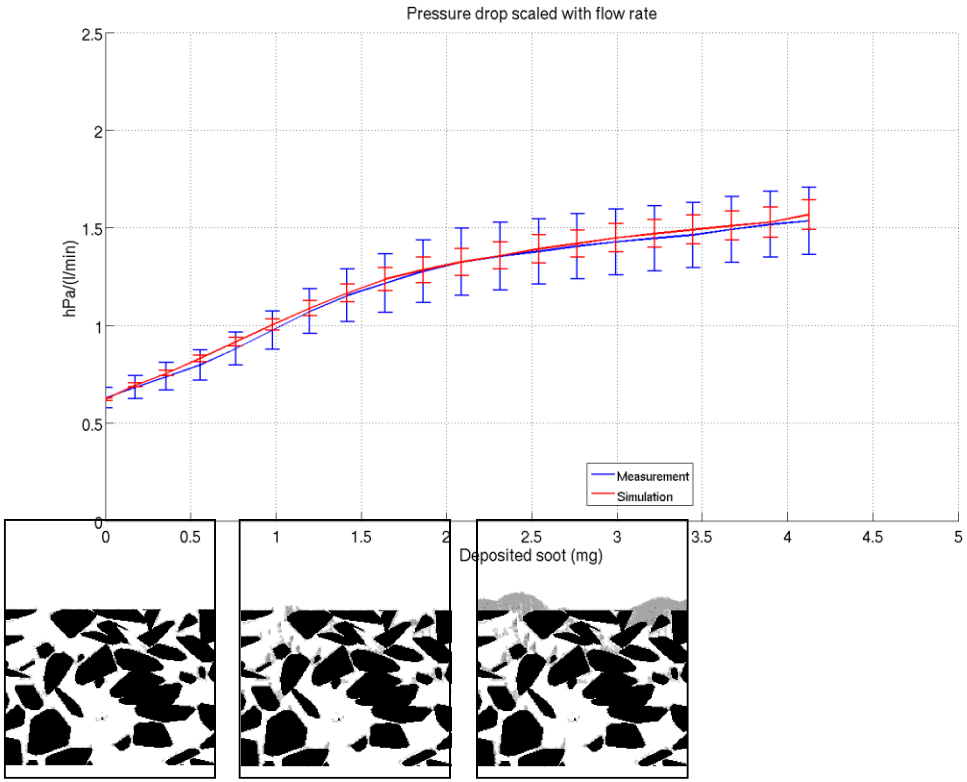
Soot deposited on a single fiber
- resolved soot simulation -
identifies maximum packing density and
corresponding flow resistivity

Soot deposited in ceramic DPF
- soot as porous media simulation –
requires maximum soot packing density and
corresponding flow resistivity

Advanced Postprocessing Video – Spatial Particle Deposition over Time



Horizontal layers



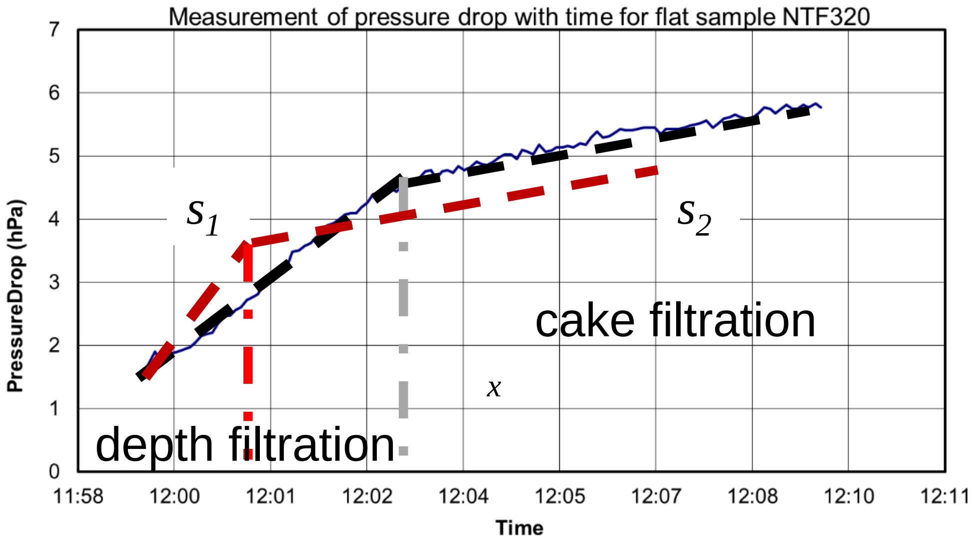
L. Cheng et al., WFC 11, 2012.

- Experimental and simulated pressure drop evolution with error bars induced by 5 measurements and 5 different realizations of the virtual structure.
- Match achieved by introducing different Brinkman parameters for depth and cake filtration.

Reduced pressure drop over time

After fast initial pressure drop increase (slope s_1, depth filtration phase)
follows long slower pressure drop increase (slope s_2, cake filtration phase)

- Matched experiment with simulations
- Shortened depth phase to lower pressure drop during cake phase
- Fraunhofer IKTS manufactured ceramic, experiment matched simulations, and patent was granted: Particulate filter, No. DE102012220181 A1 [http://www.google.com/patents/DE102012220181A1?cl=en]

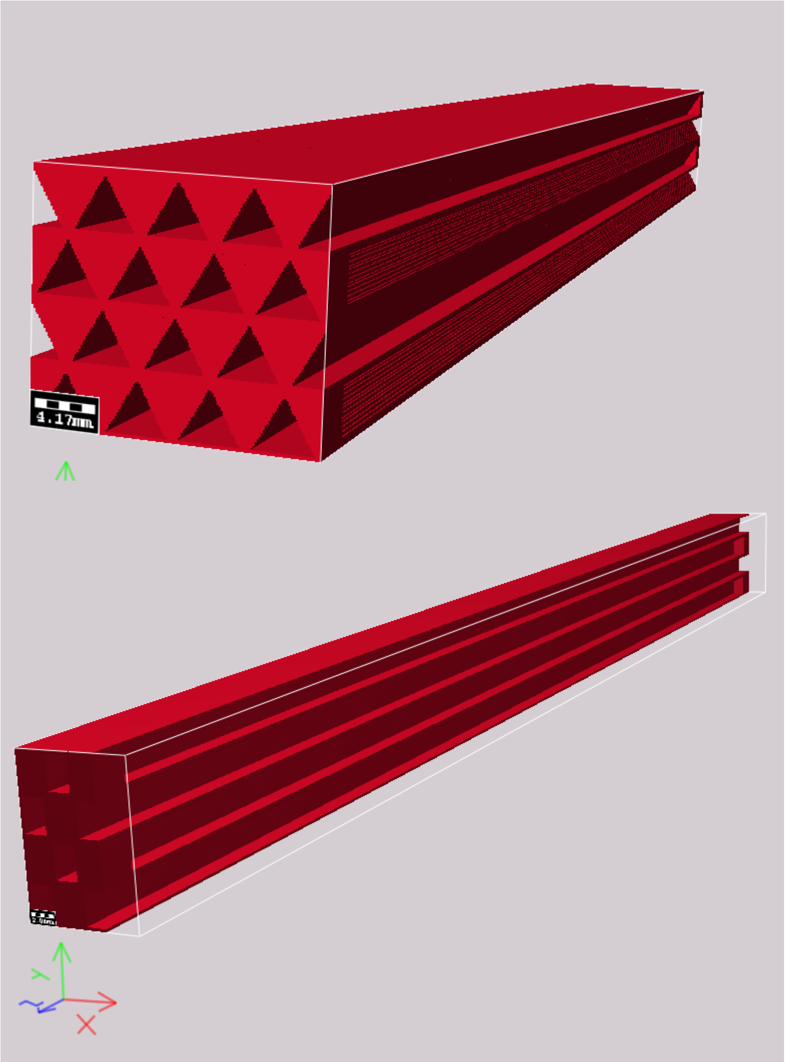


Honeycomb structures (DpfGeo)

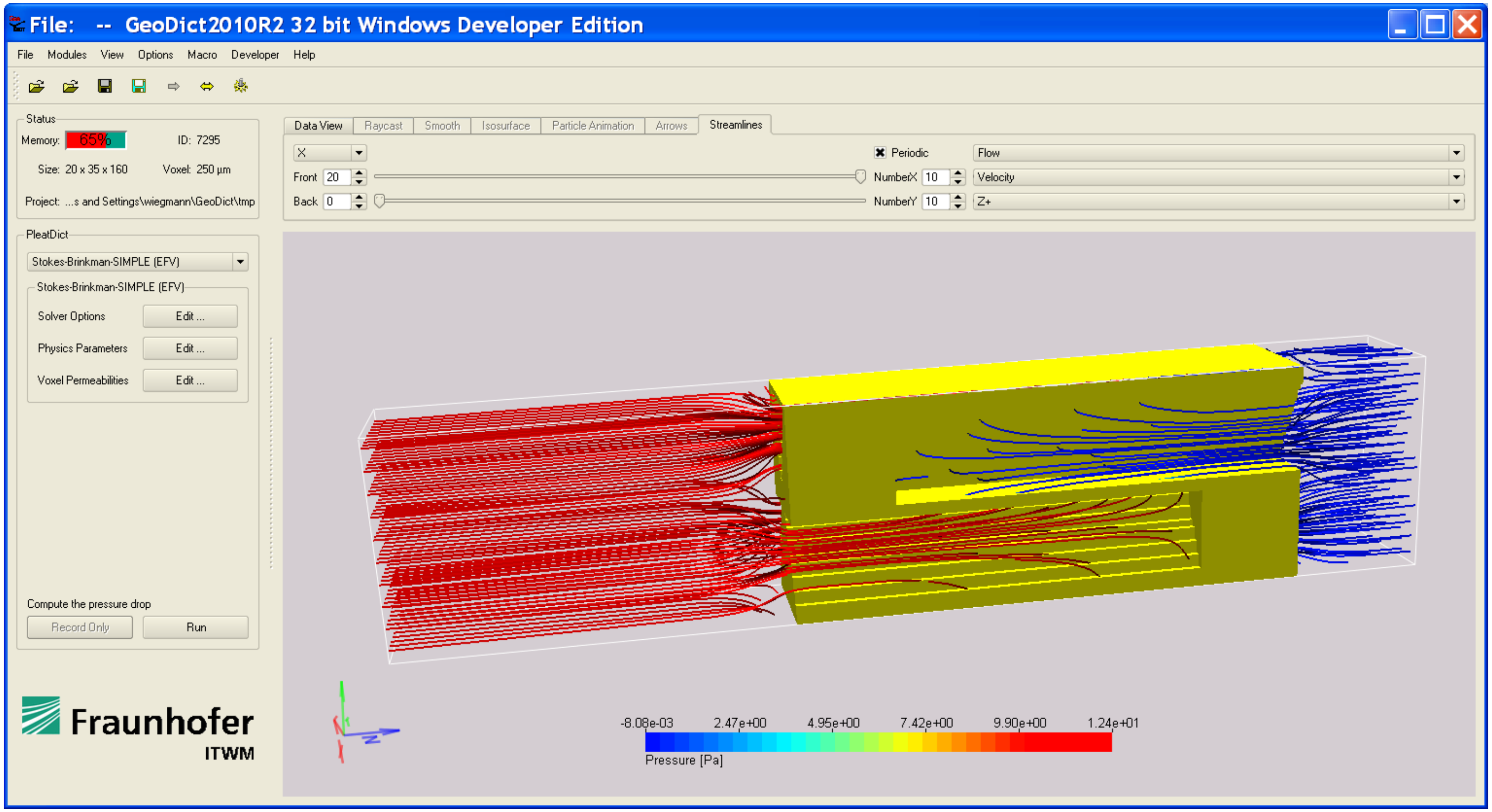
Triangular and square

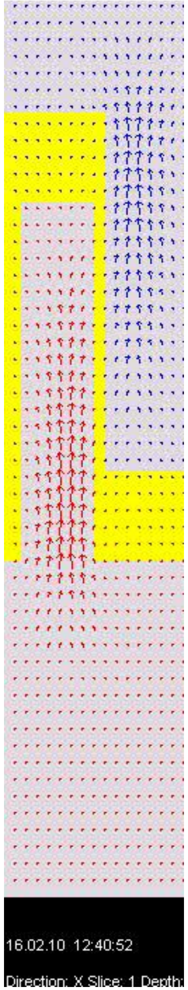
honeycomb structures

- Zhang, X. *Numerical study of flow and pressure characteristics for Diesel particulate filters with square and triangle channels*. Filtration 8 (3), 2008.

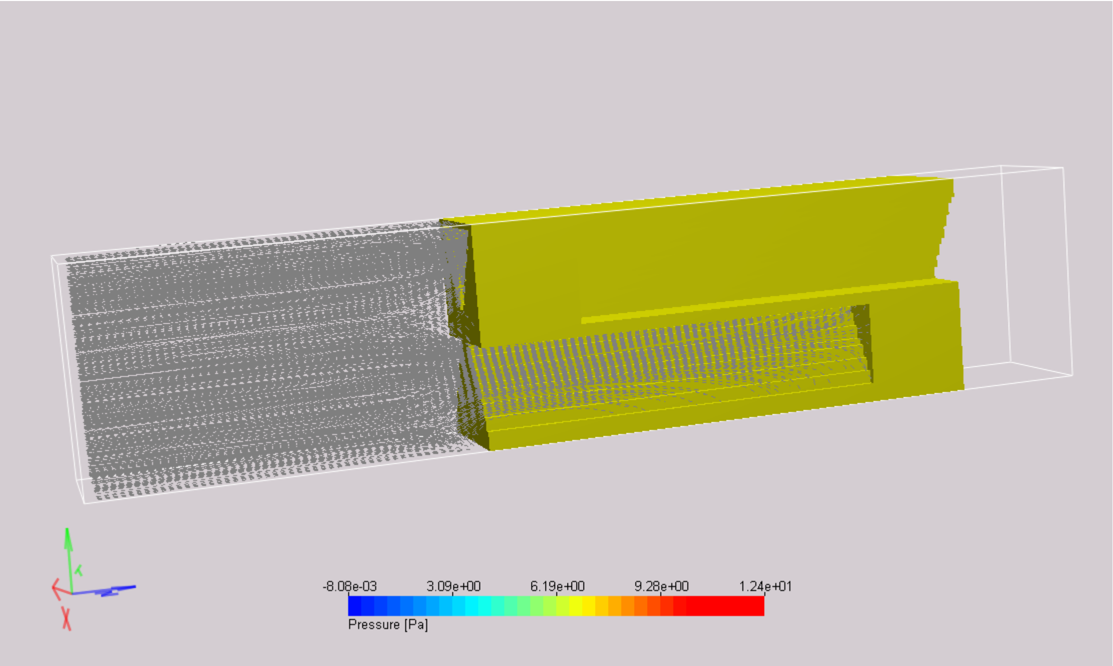


Streamlines and velocity field (PleatDict)





Paths of 0.1µm (filtered) particles



Design of Fibrous Filter Media Based on the Simulation of Pore Size Measures

Simulation of mercury intrusion porosimetry (MIP)
Simulation of liquid extrusion porosimetry (LEP)
Simulation of maximum inscribed sphere (MIS)

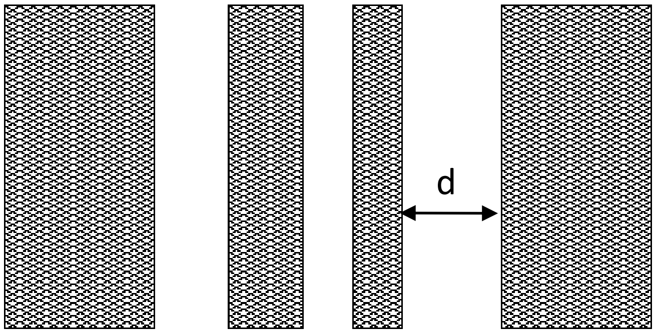
- FILTECH, Wiesbaden

- Jürgen Becker,
- Andreas Wiegmann,
- Volker Schulz

Fraunhofer ITWM Institut Techno- und Wirtschaftsmathematik

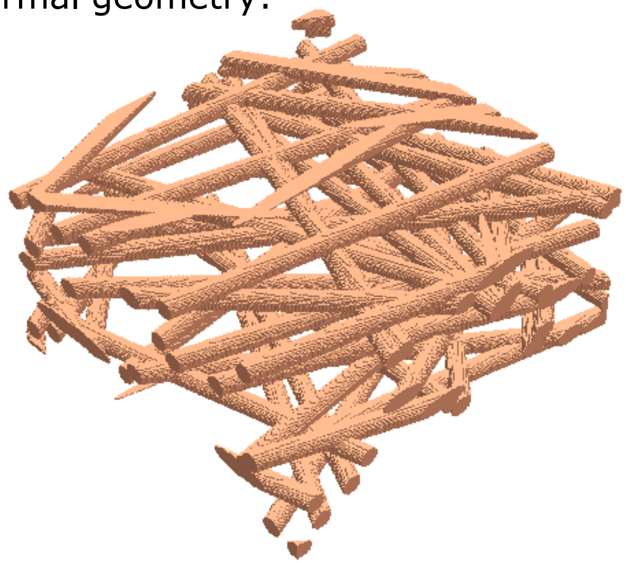
Pore Size Distribution

simple geometry:



Pore sizes well defined and easy to measure

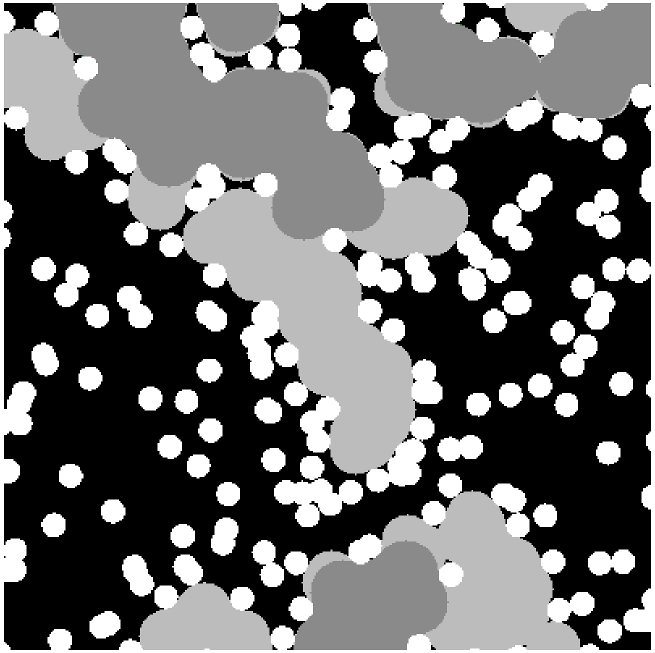
normal geometry:



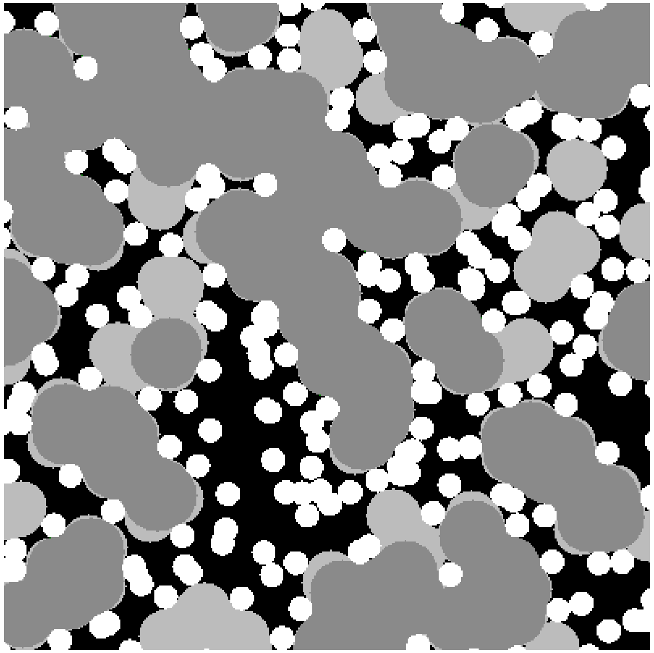
How to define a pore size ?

What is measured?

Mercury intrusion porosimetry simulation (MIP) vs. maximum inscribed sphere (MIS) simulation



MIP

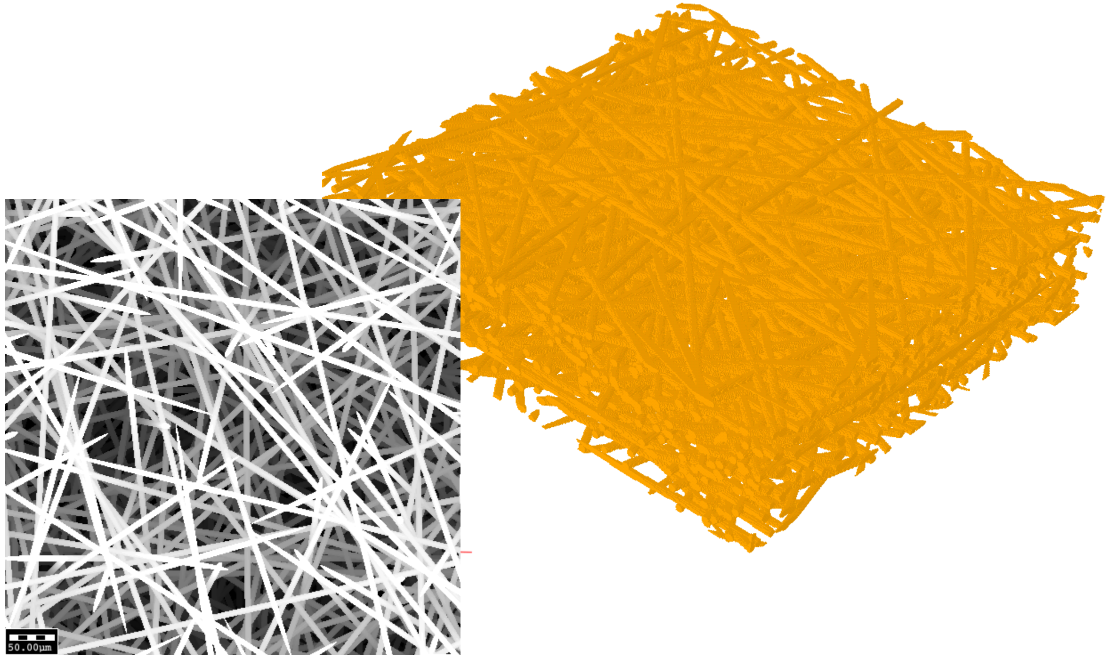


MIS

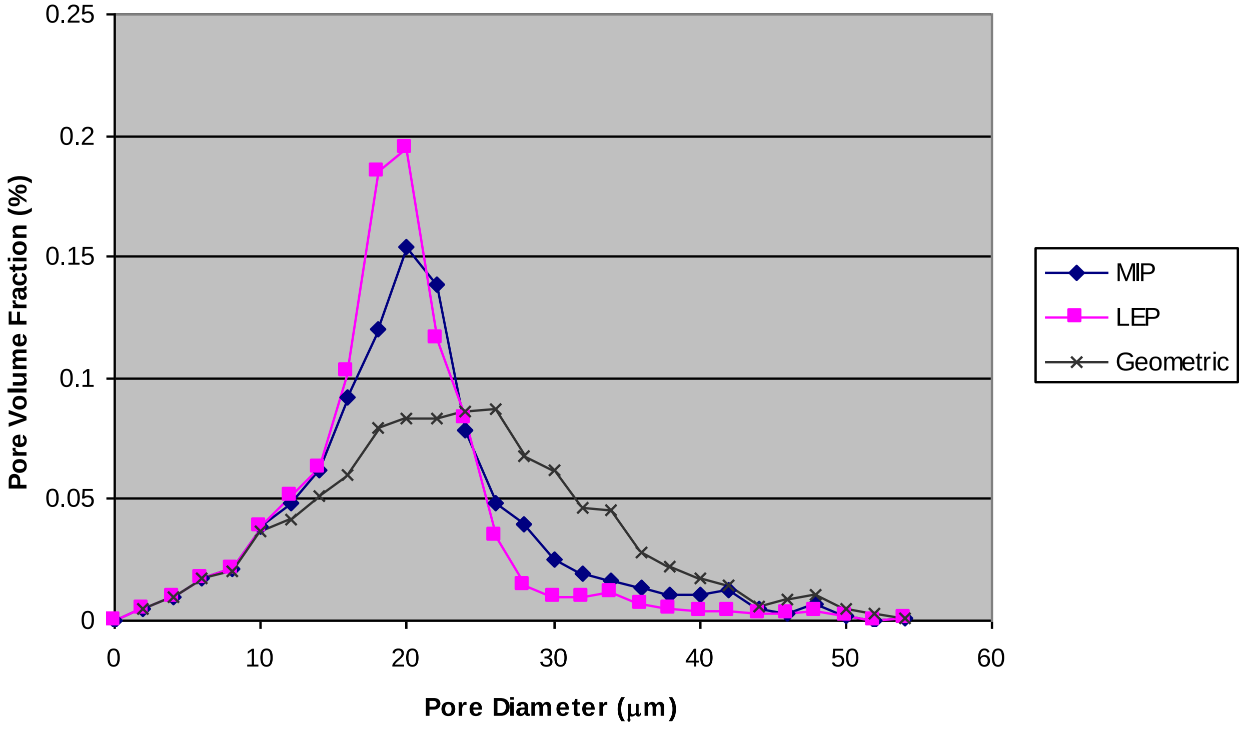
3D sample structure

digitally created 3D fibre structure

- fibre diameter 7μm
- porosity 82%
- highly anisotropic

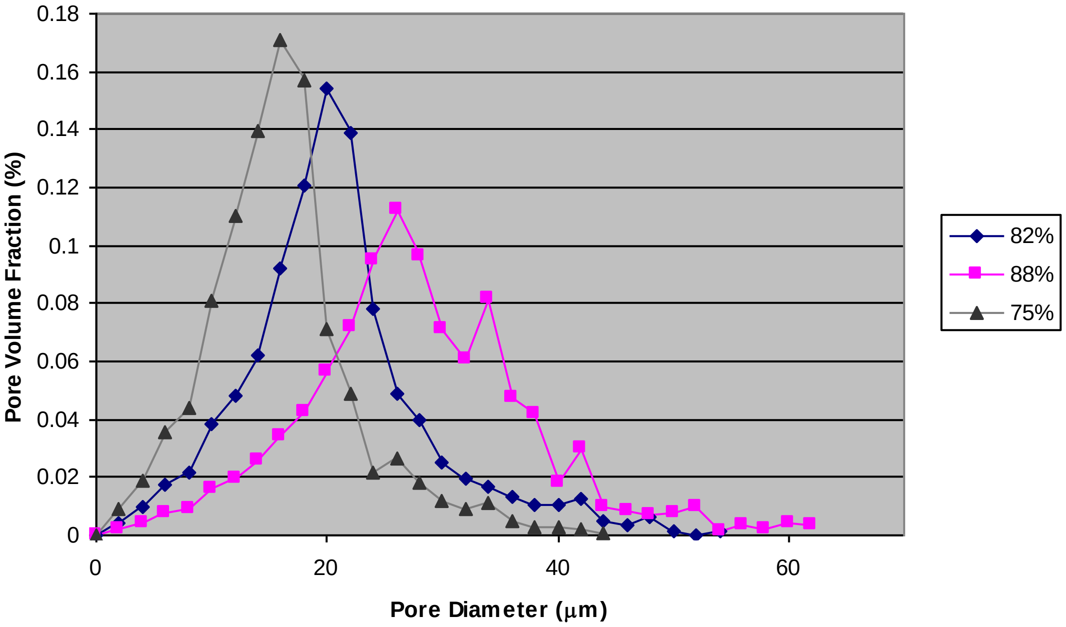


Results of the simulation



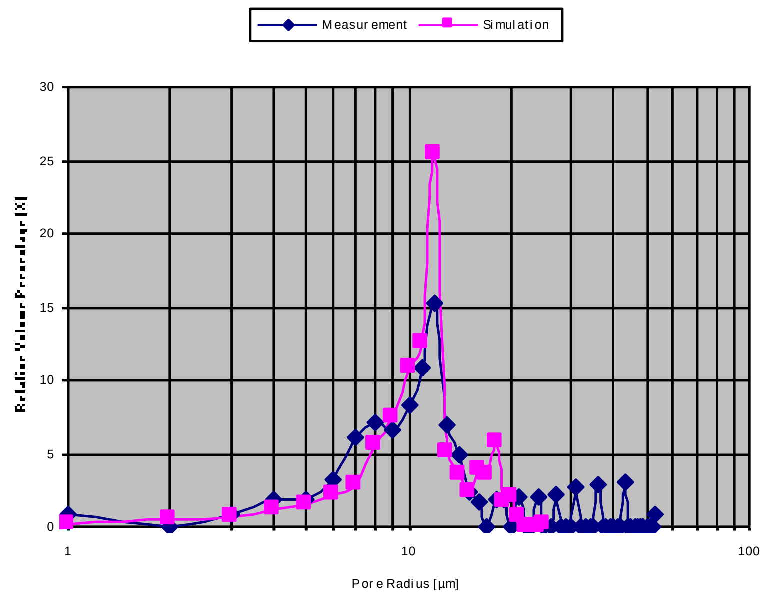
Dependence of Pore Size Distribution on design parameters (example)

- media with porosities 75%, 82%, and 88%.
- chart shows results of simulated MIP.

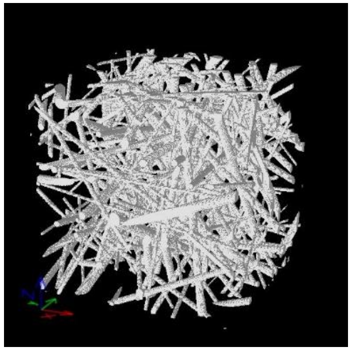


Comparison of measurement and simulation

- Measurement: MIP



- Simulation:
  - digitally created fibre structure using known values for porosity and fiber thickness distribution.
  - simulated MIP



Summary / References

- Different measurement techniques measure different "Pore Size Distributions"
(see A. Jena, K. Gupta, Fluid Particle Separation J. 4, 2002, pp. 227-241)
- Mercury intrusion porosimetry (MIP) can be simulated
- Liquid extrusion porometry (LEP) can be simulated
- Both result in fewer large pores than maximum inscribed sphere (MIS, purely geometric) approach due to requirement of connectivity with the domain boundaries
- Largest simulated through pore agrees extremely well with glass bead tests, see work by Haver & Boecker and Whitehouse Scientific

Filtration simulation
Method and Algorithm

Filter Efficiency simulations

Basic idea:

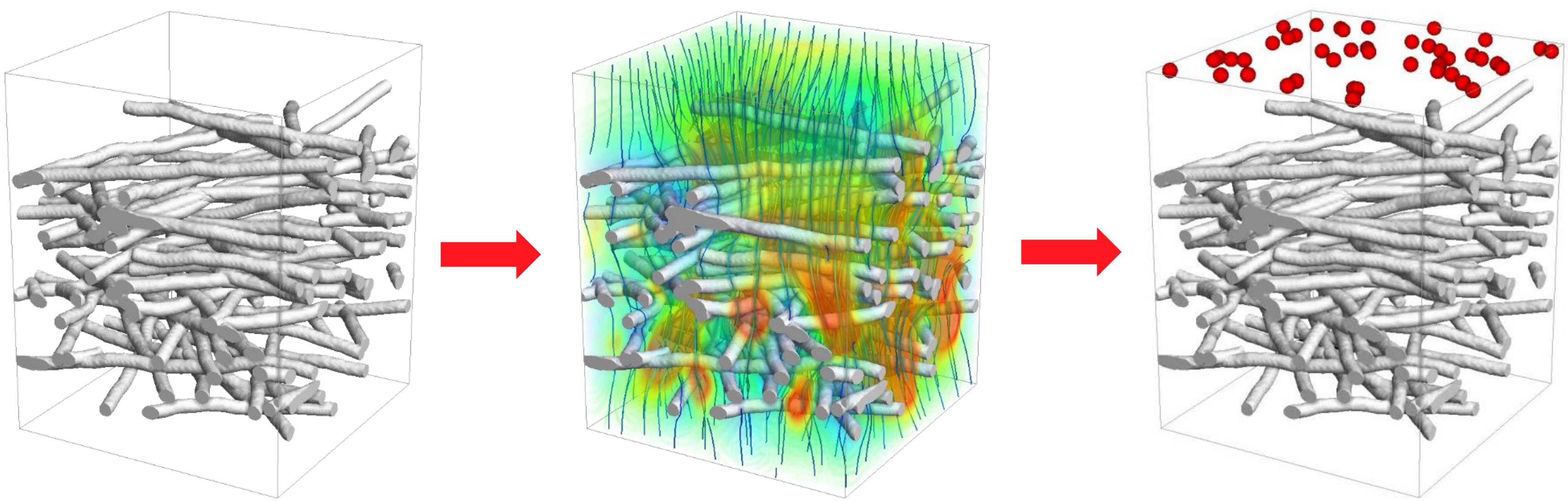
1. Filter media model
2. Determine flow field
3. Track particles (filtered or not?)

Randomness:

- Starting positions
- Brownian motion

Result:

- Percentage of filtered particles



Flow simulation
Stationary Navier-Stokes flow

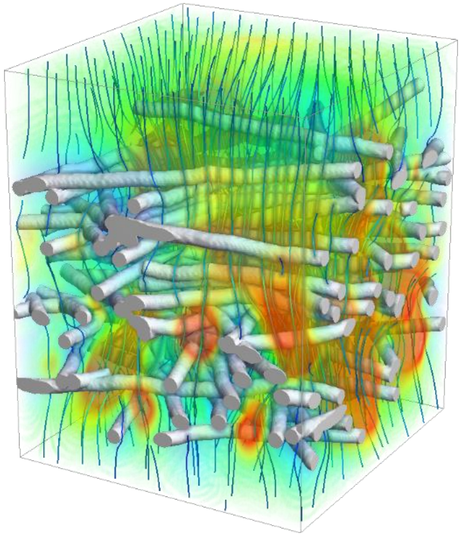
$-\mu\Delta\vec{u} + \rho(\vec{u}\cdot\nabla)\vec{u} + \nabla p = 0$ (momentum balance)

$\nabla\cdot\vec{u} = 0$ (mass conservation)

$\vec{u} = 0$ on Γ (no-slip on surface)

$P_{in} = P_{out} + const$ (pressure drop is given)

$\vec{u}$: velocity
p: pressure
μ: dynamic viscosity
ρ: fluid density



Tracking particles in a flow field

Impulse — Stokes Drag — Electrostatic Force

$$m\frac{d\vec{v}}{dt} = 6\pi\mu\frac{R}{C_c}\left(\vec{u} - \vec{v} + \sqrt{2D}\frac{d\vec{W}(t)}{dt}\right) + Q\vec{E}$$

Brownian Motion

Cunningham Corrected Particle Radius

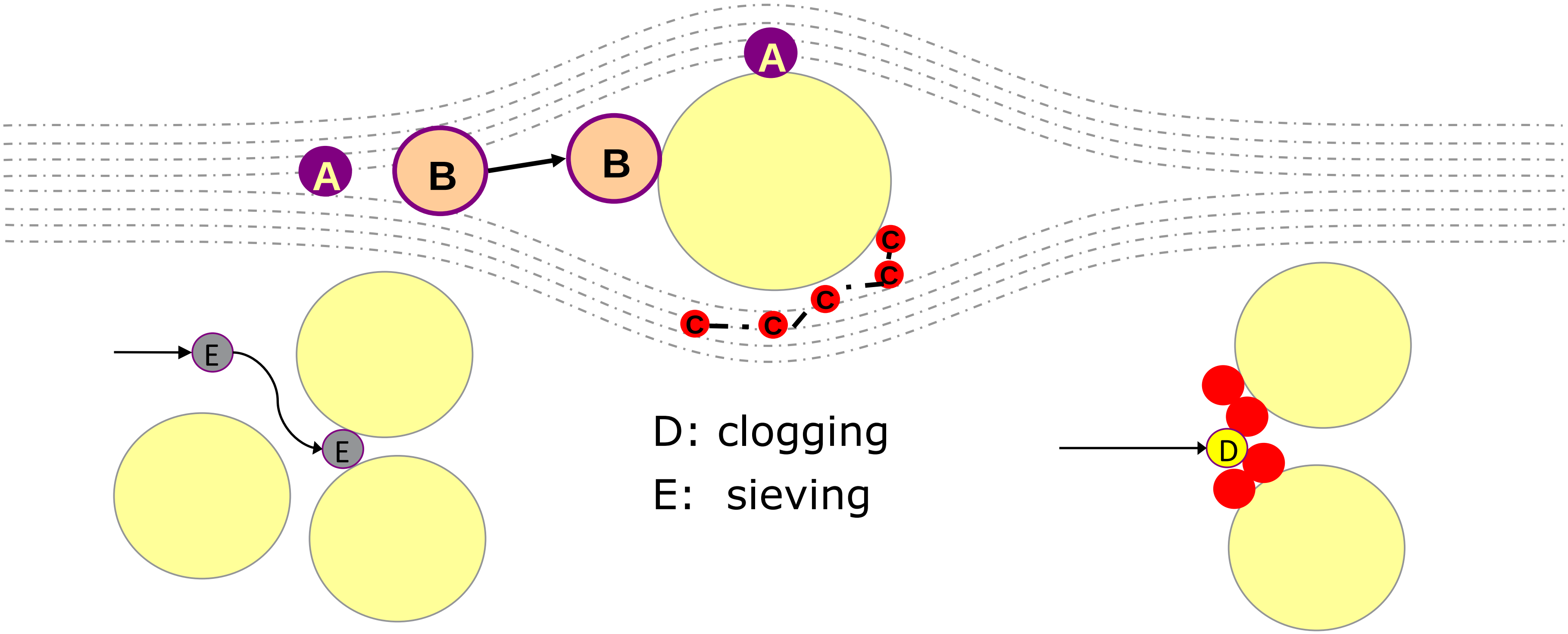
$\vec{v}$	: particle velocity [m/s]	μ	: dynamic viscosity [kg/m·s]
$\vec{u}$	: fluid velocity [m/s]	Q	: particle charge [C]
R	: particle radius [m]	E	: electric field [V/m]
C_c	: Cunningham correction	D	: Diffusivity [m²/s]
m	: particle mass [kg]	$d\vec{W}$	: 3D Wiener process

Filtration effects I

A: direct interception

B: inertial impaction

C: diffusional deposition



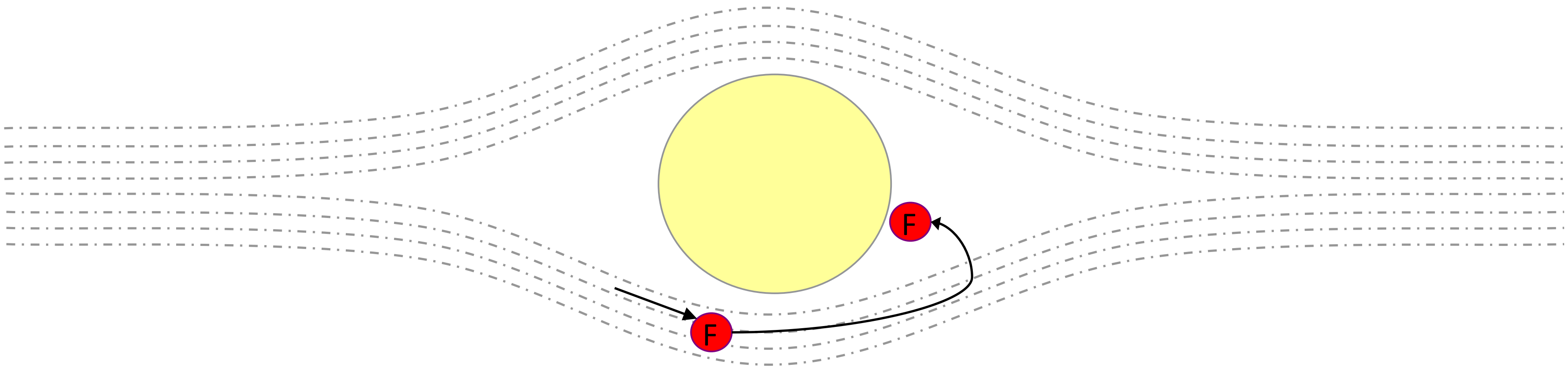
D: clogging

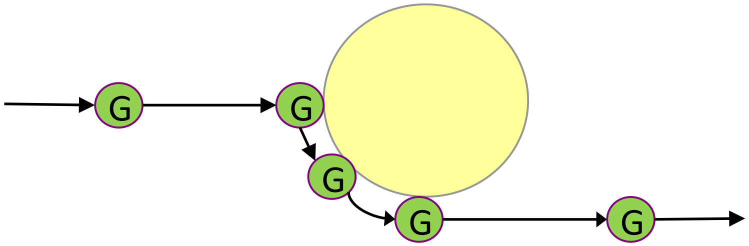
E: sieving

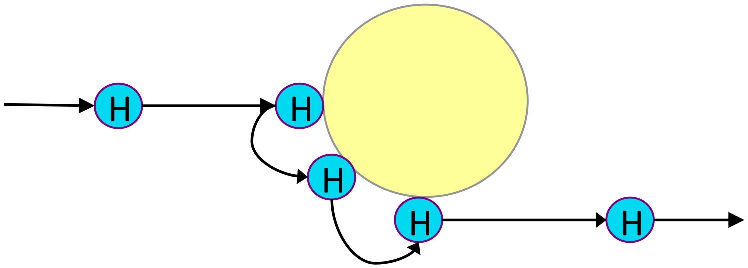
Andreas Wiegmann
AFS 2017, Louisville
11 April 2017

Filtration effects II and modes of particle motion

F: electrostatic attraction



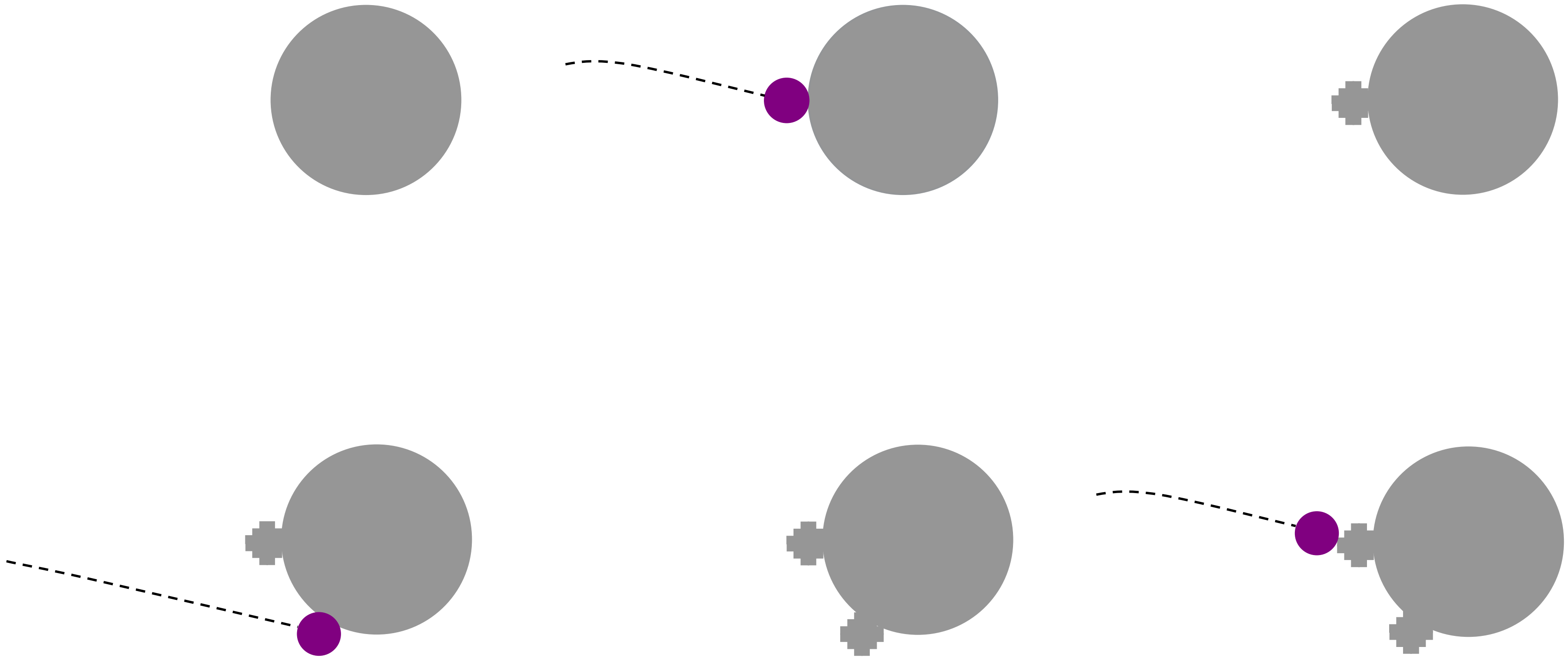




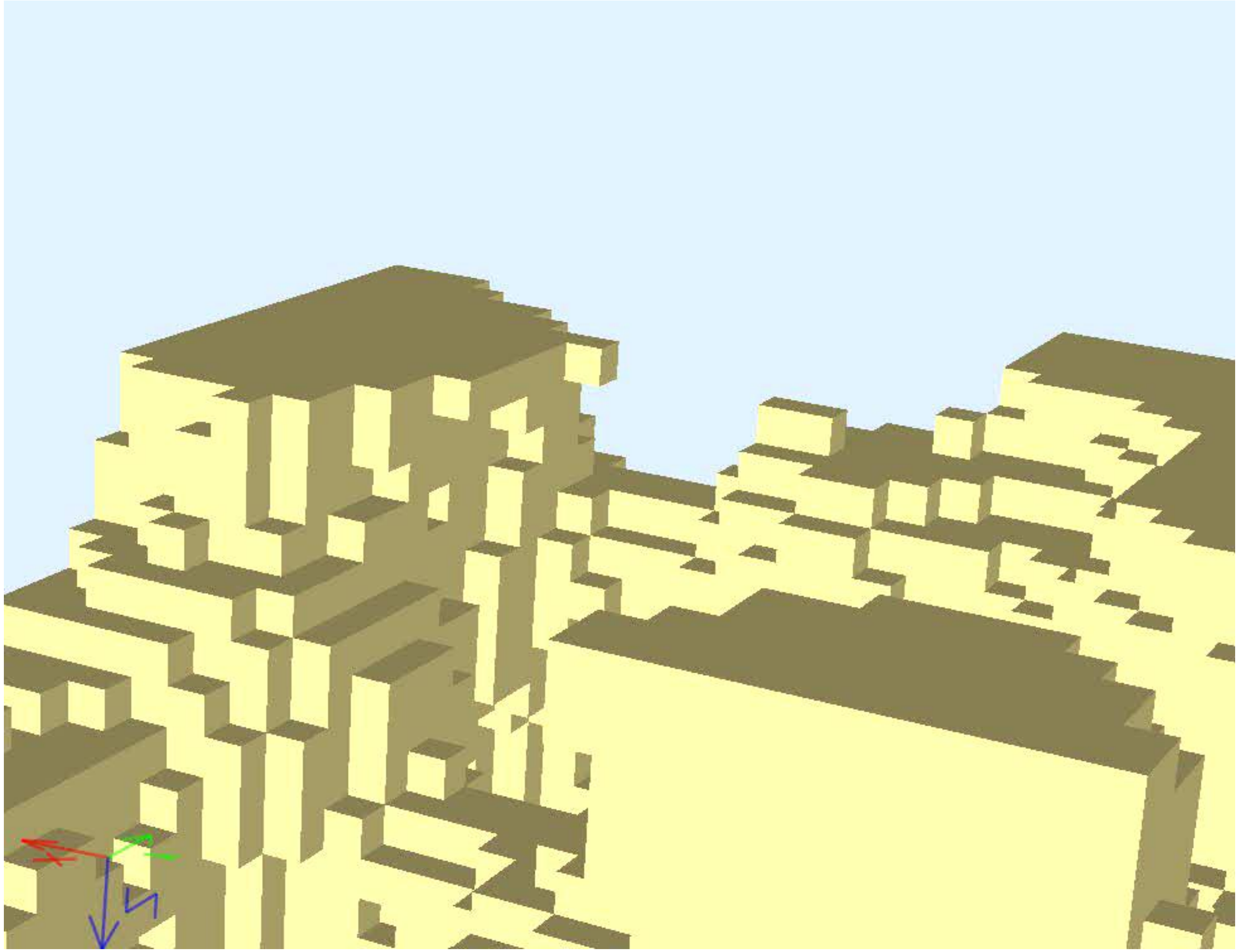
G: Slide

H: Bounce

Filtration of resolved particles
grid cells can be solid or empty



Soot forming cake
- detail of the beginning

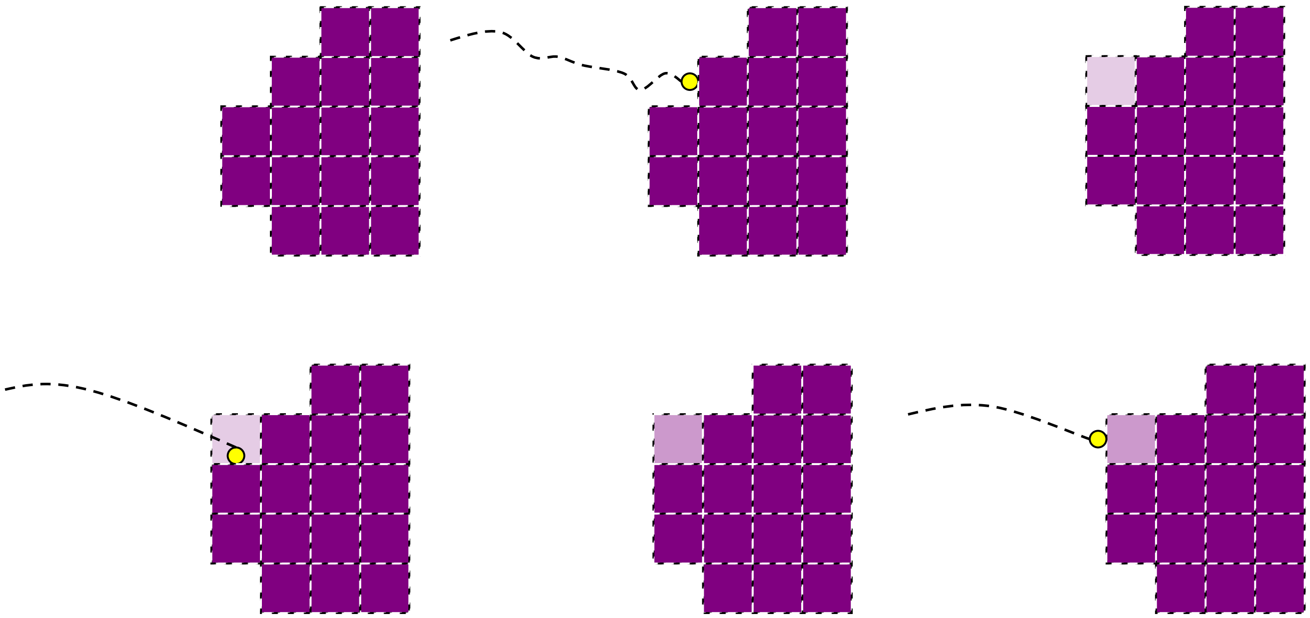


Filtration of unresolved particles
grid cells can be solid, empty or porous (& permeable)

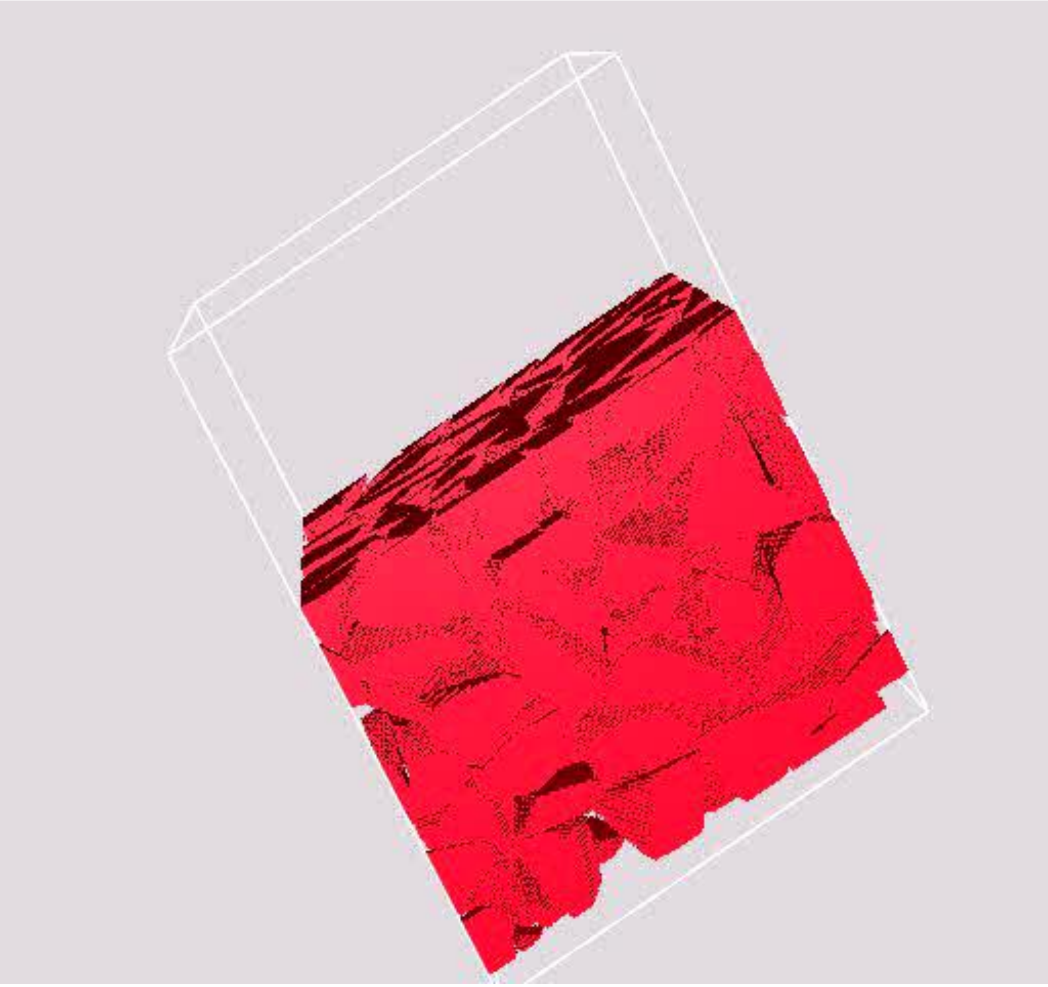
Soot particles are much smaller than the computational grid.

When they deposit, they do not fill the computational cell, but rather form a permeable media inside and on top of the ceramic filter.

We control how much a cell can get filled, and how much resistivity to the flow the cell will have, depending on the degree of filling.



Soot filtration
- millions of particles per time step!



Conclusions and Outlook

Conclusions

- We saw 3d models for filter media, pleats and whole filters, where the media models could also result from µCT-scans of existing media
  - Cellulose, glass and synthetic fibers
  - Ceramics
  - Open-cell foams
  - Weaves
- On the models one can predict
  - Pore Size measures
  - Pressure drop, flow resistivity, permeability,
  - Filter Efficiency
  - Filter Life Time / Dust Holding Capacity
- Simulations, combined with experiments, can lead to
  - New knowledge, such as understanding of re-entrainment
  - Quantification of phenomena, such as effects of layers
  - And also patents and long-term commercial benefits

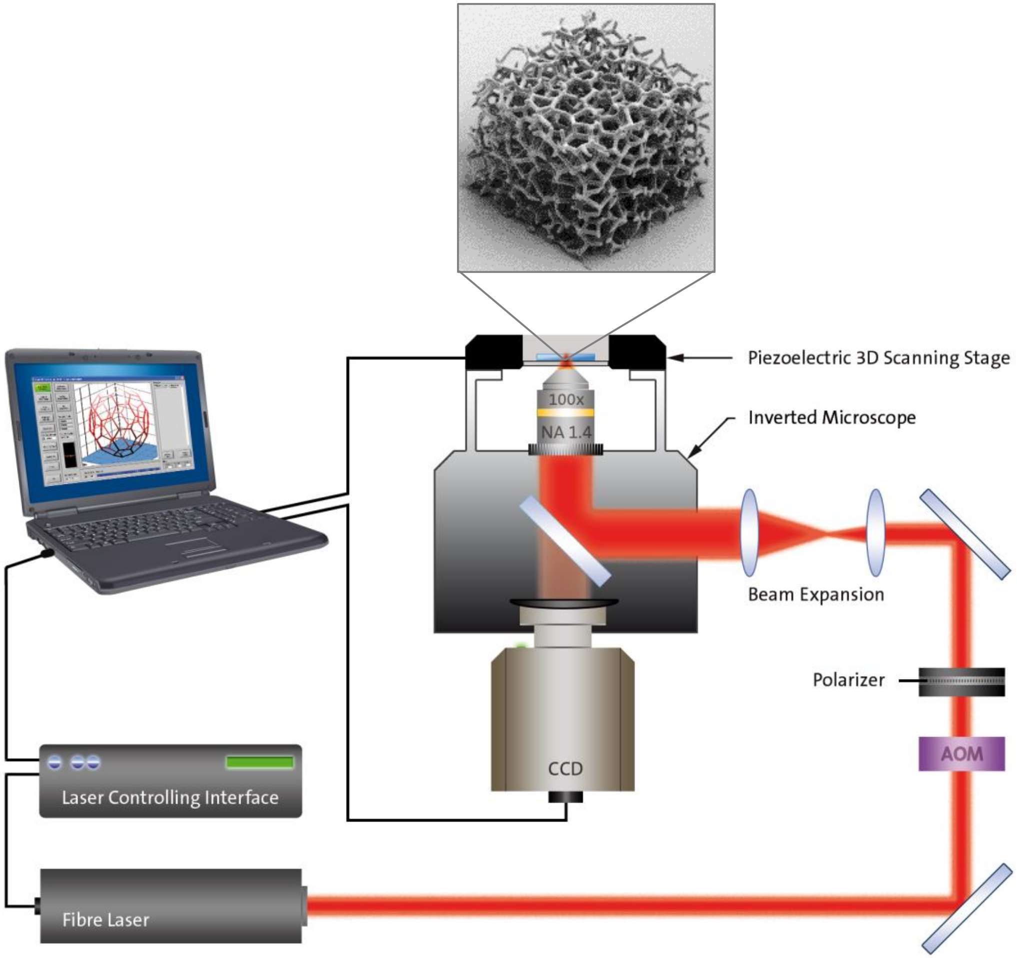
Outlook

- Material-scale Simulation is here to stay – more computer power and higher resolution in 3d imaging will lead to better and better material scale models than can be run in less and less time.
  - Math2Market is exploring the possibility to use cloud computing, for example.
- The material scale models will produce output that will be usable automatically in pleat-scale and filter-scale simulations.
  - For structural mechanics simulations, Fraunhofer ITWM and Math2Market are already creating UMATS from the material scale that can be used in ABAQUS simulations on the part-scale. This will be transferred to filtration phenomena as well.
- The more we work on simulation, the more we appreciate experiments, and the more we realize how much more work still lies ahead …
  - Example: Additively manufactured filter media with fiber diameter around 1µm

Additive Micromanufacturing

Center for Materials Characterization and Testing

- Printable Materials
  - Acrylate-based photoresists (IP resists)
- Local exposure via ultrashort laser pulses and two-photon absorption
- Crosslinking of liquid photoresist only in the very focus of the laser
- Wet chemical development removes unexposed photoresist
- Feature size < 150 nm
- Resolution < 600 nm



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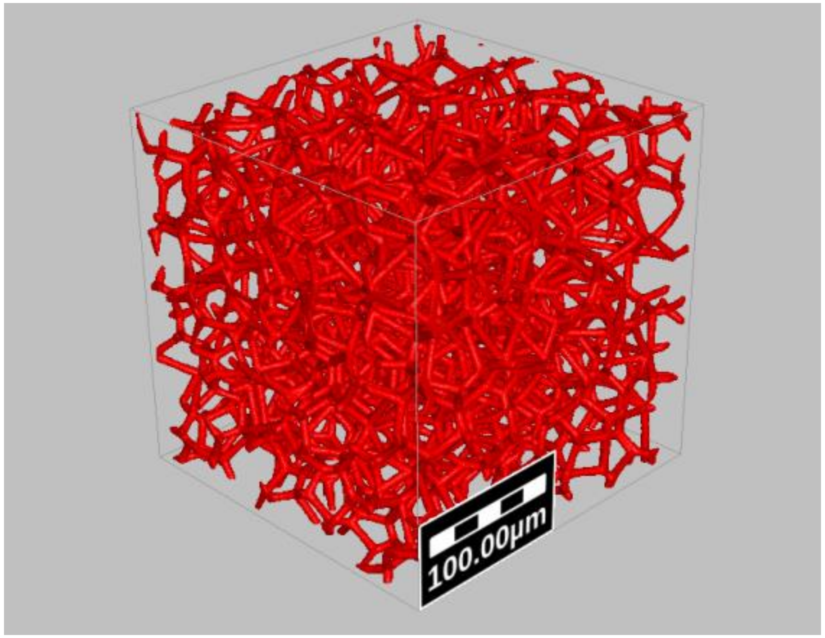
Additive Micromanufacturing

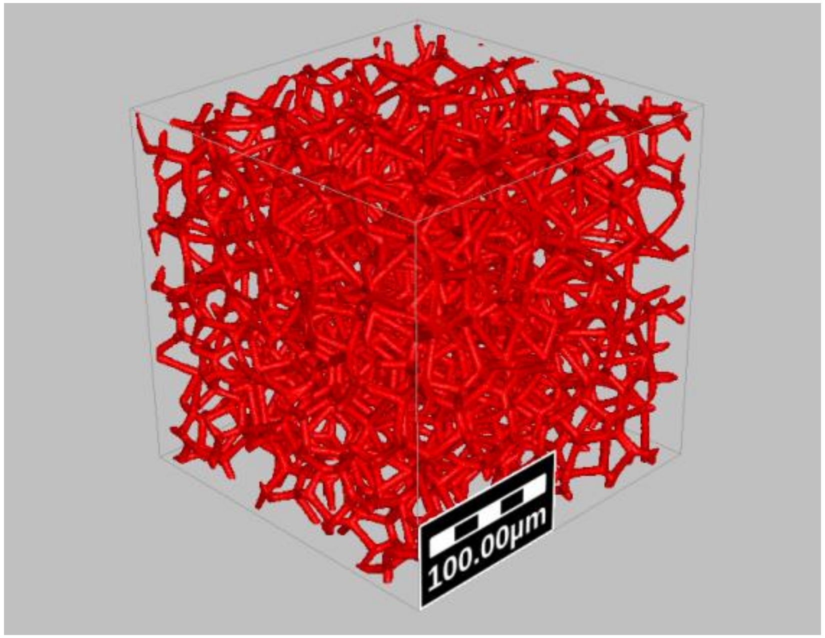
Application example: computer-optimized filtration media

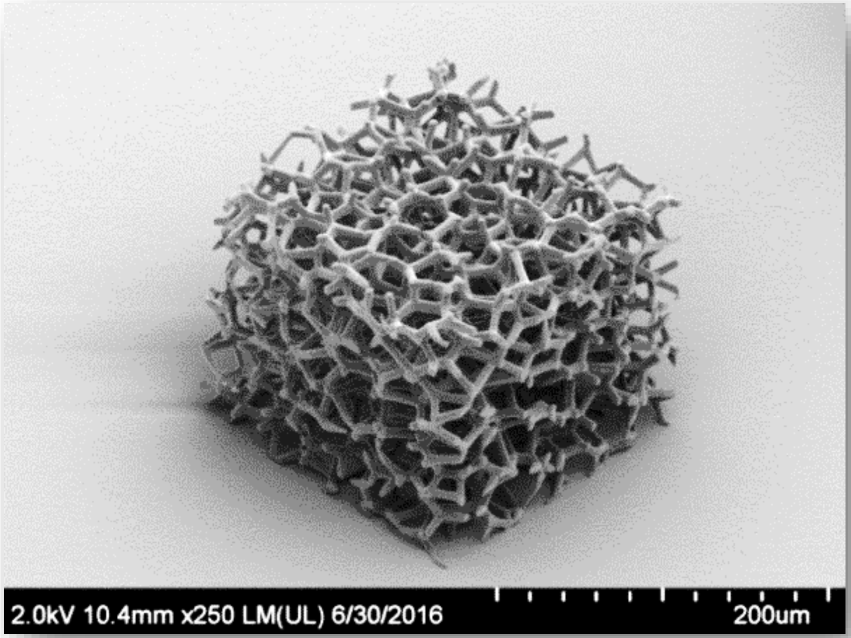


Fraunhofer ITWM

Additive Micromanufacturing

Application example: computer-optimized filtration media

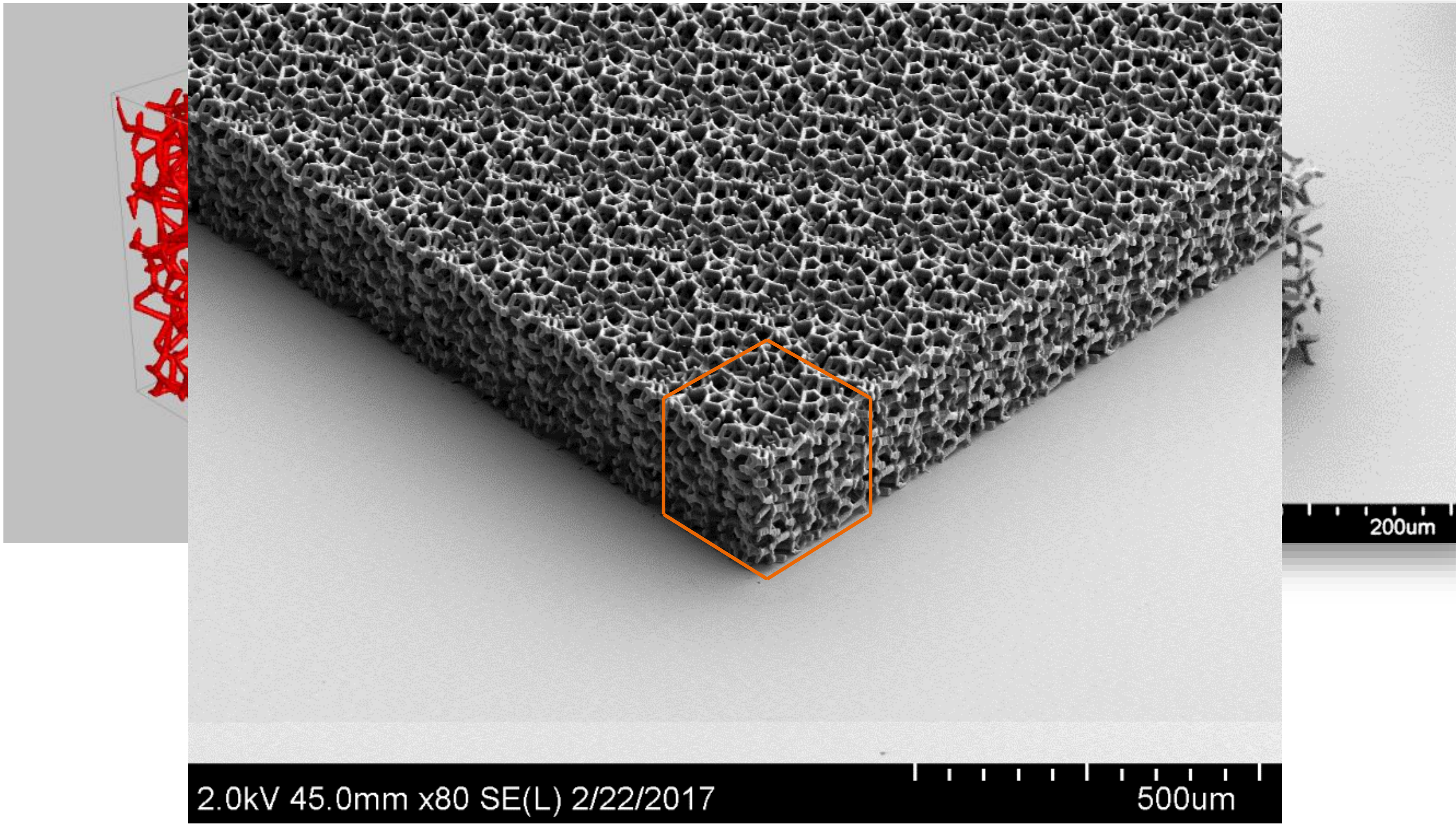




Fraunhofer ITWM

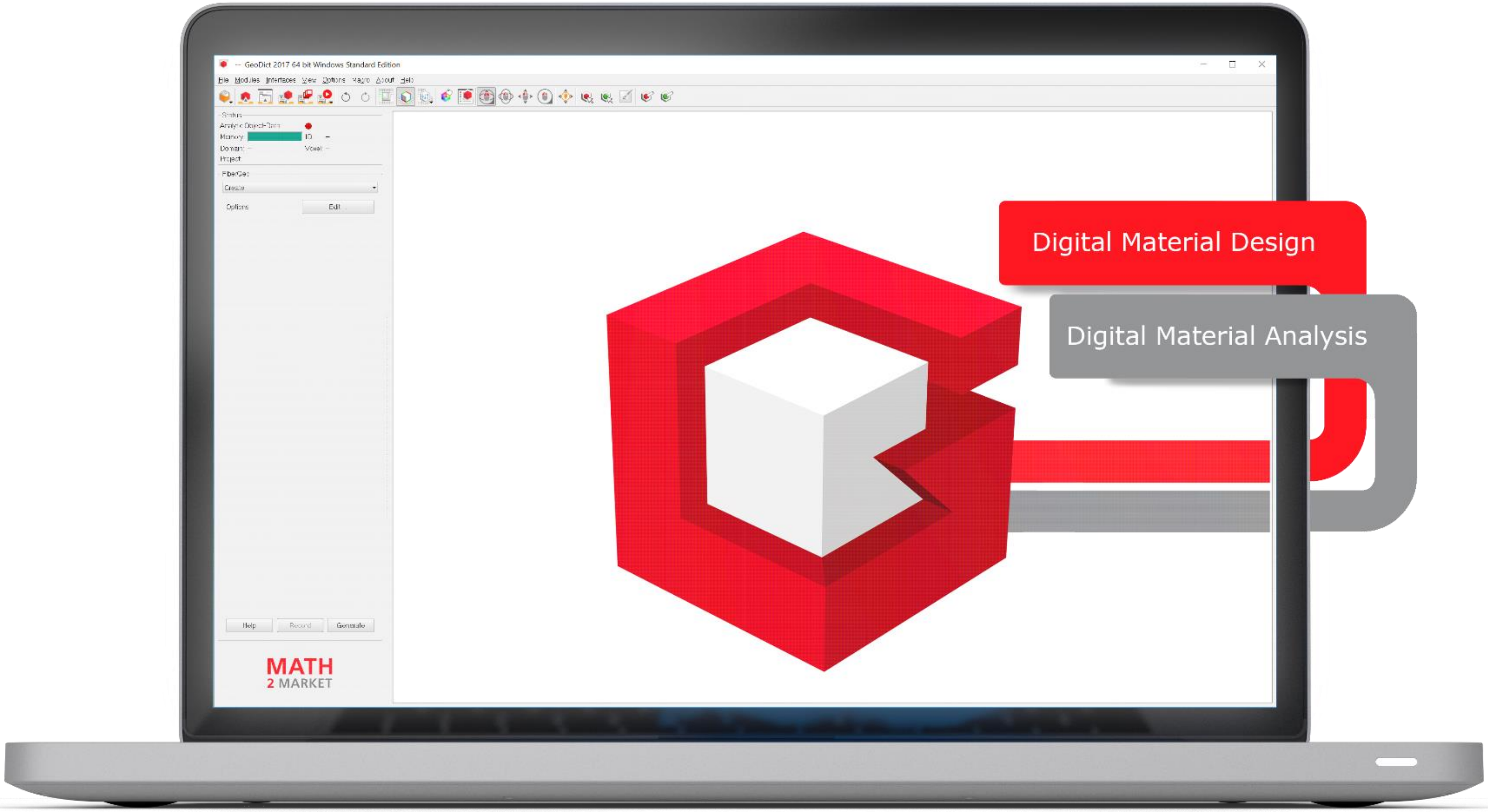
Additive Micromanufacturing

Application example: computer-optimized filtration media



Fraunhofer ITWM

Thank you for your time and attention. Please feel free to ask questions...



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