

---

# Design of filter media via simulation

---

Andreas Wiegmann, PhD

[wiegmann@itwm.fhg.de](mailto:wiegmann@itwm.fhg.de)

Dipl. Math. Stefan Rief

[rief@itwm.fhg.de](mailto:rief@itwm.fhg.de)

Priv. Doz. Dr. Arnulf Latz

[latz@itwm.fhg.de](mailto:latz@itwm.fhg.de)

Symposium >> Textile Filters <<

Chemnitz, March 7th, 2006.



Fraunhofer  
Institut  
Techno- und  
Wirtschaftsmathematik

## **I. Virtual Material Design Cycle**

## **II. Filter Media**

## **III. Fluid & Electric Field**

## **IV. Dirt model & dirt motion**

## **V. Deposition**

## **VI. Life time**

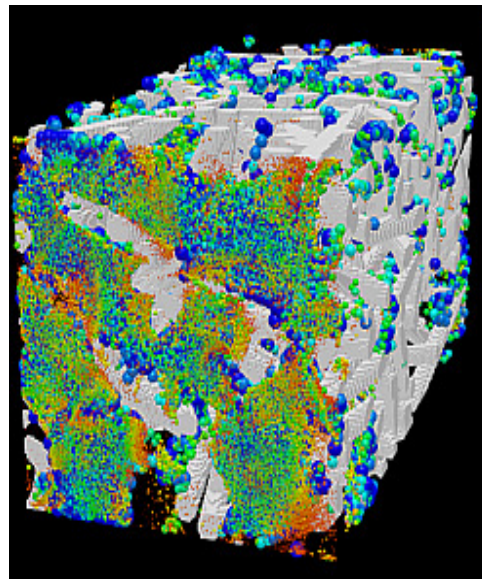
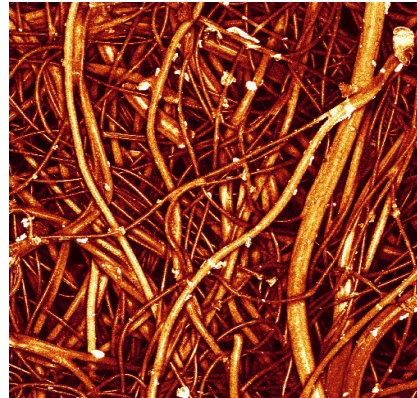
## **VII. Nano model**

## **VIII. Summary**

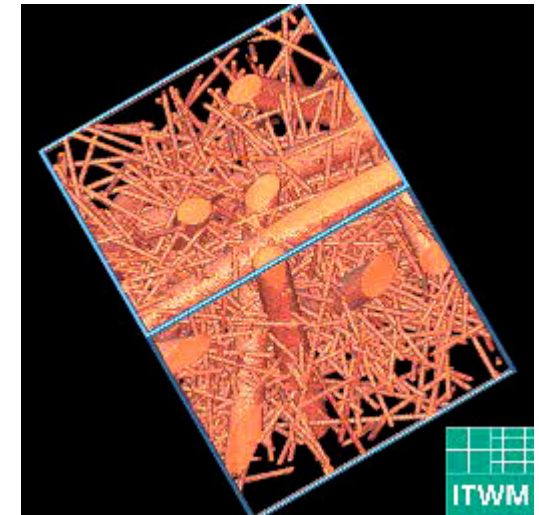
# I. The Virtual Filter Material Design Cycle

1. Identify parameters for real, existing material
  - ↓
  2. Generate volume image for parameters
  - ↓
  3. Solve Stokes(-Brinkmann) equations
  - ↓
  4. Solve electric potential
  - ↓
  5. Solve particle motion & deposition
  - ↓
  6. Compute filter efficiency, pressure drop/ filter life time
  - ↓
  7. Modify material parameters
- 

REM



Generated



Clogged nonwoven

**I. Virtual Material Design Cycle**

**II. Filter Media**

**III. Fluid & Electric Field**

**IV. Dirt model & dirt motion**

**V. Deposition**

**VI. Life time**

**VII. Nano model**

**VIII. Summary**

## II. What constitutes ITWMs designable Virtual Materials?

---

The real media, **porous** or **composite** [e.g. **nonwoven** vs. **carbon fiber-enforcement**]

The mathematical **model** with (few) parameters [e.g. fiber diameter, etc.]

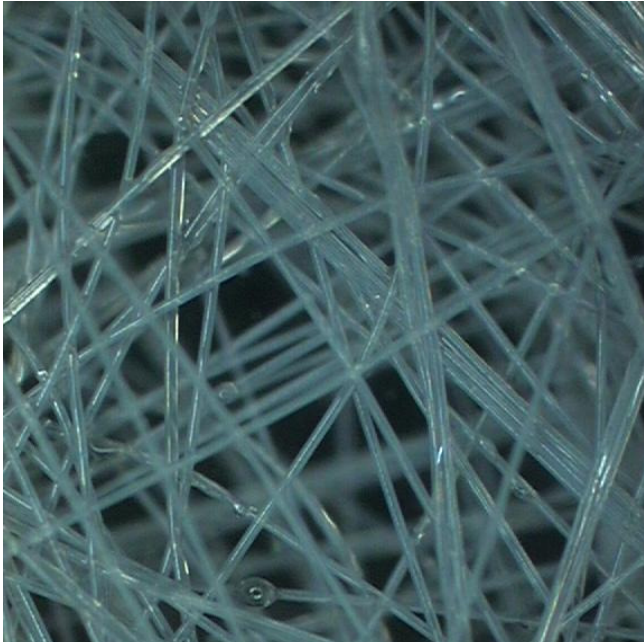
The **Realizations** in volume images, independent of the model

The **Validation**

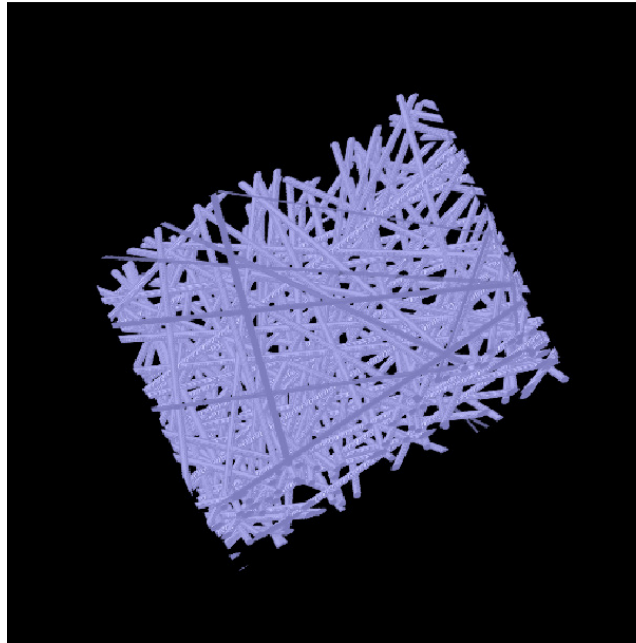
- inspection [2d & 3d visualization, comparison with microscopy & tomography]
- geometric analysis [e.g. porosity, pore size distribution, etc.]
- agreement of computed properties for existing media

The **Design**; based on model parameters, not the volume images

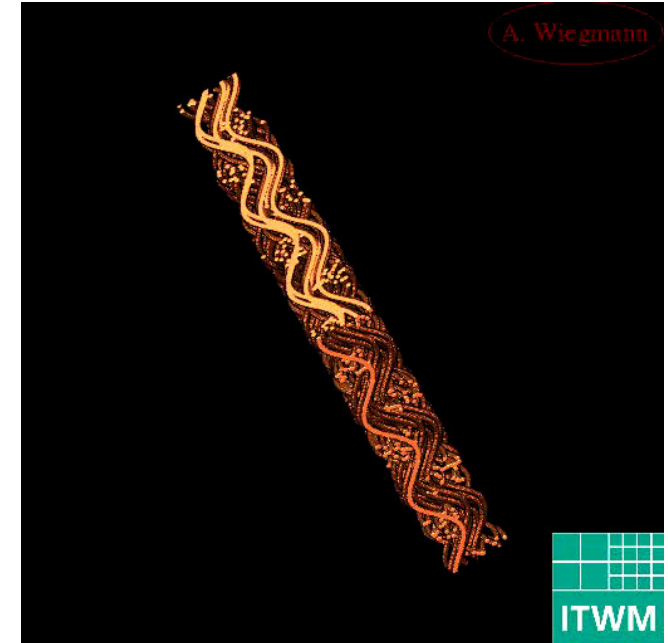
## II. Material Models for Nonwoven, Woven & Layers



Microscopy



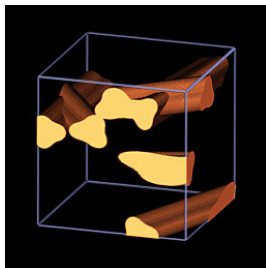
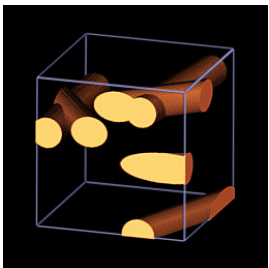
Nonwoven model



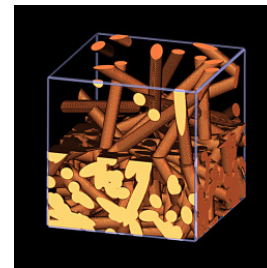
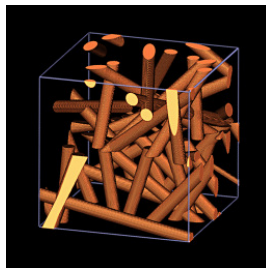
Multifilament woven model

Possible variations: for example

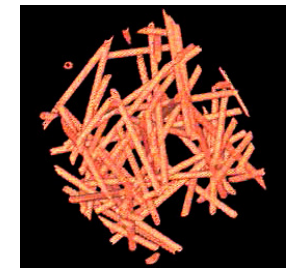
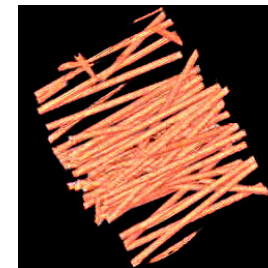
- Cross sections



- Layers



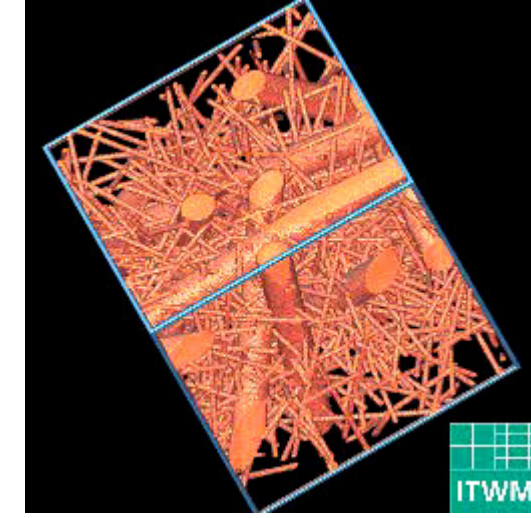
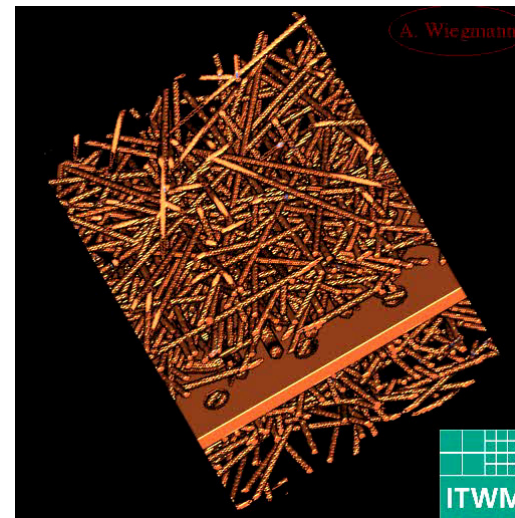
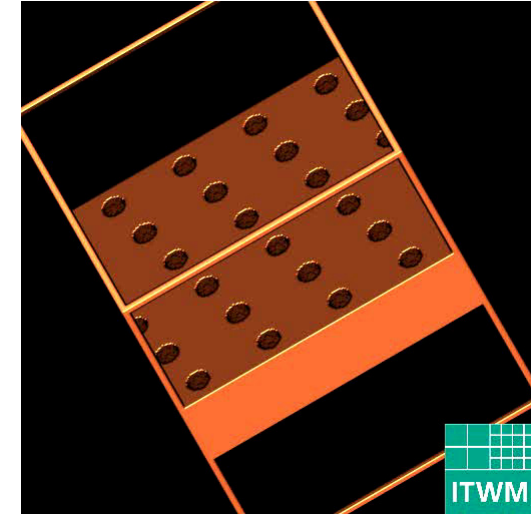
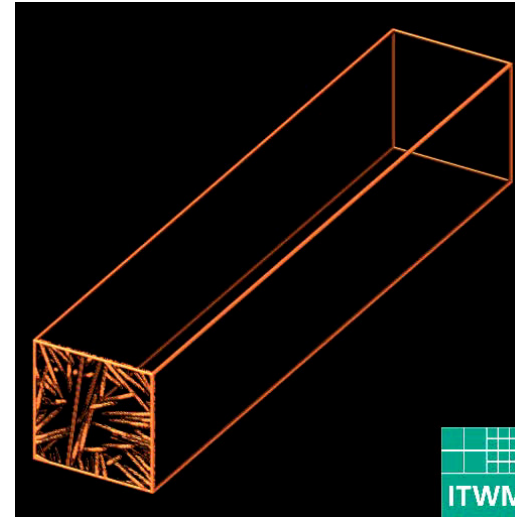
- Anisotropy





## II. Simulation and Design Parameters for Filter Media

1. Nonwoven model
2. Sinter model
3. Layers
4. Layer thicknesses
5. Porosity
6. Fiber diameters
7. Fiber anisotropy
8. Fiber shapes
9. Fiber overlap
10. Fiber crimp
11. Fiber length
12. ...



**I. Virtual Material Design Cycle**

**II. Filter Media**

**III. Fluid & Electric Field**

**IV. Dirt model & dirt motion**

**V. Deposition**

**VI. Life time**

**VII. Nano model**

**VIII. Summary**



### III. Fluid & Electric Field:

---

For very **sparse particles**, the **influence** of the particles **on the flow field and on the electrical field** can be neglected.

The fluid enters the model through its **viscosity  $\mu$** . For example,

Oil at -25°C :  $\mu = 1.50\text{e}+0 \text{ kg}/(\text{m s})$

Blood at 22°C :  $\mu = 2.00\text{e}-2 \text{ kg}/(\text{m s})$

Air at 20°C :  $\mu = 1.84\text{e}-5 \text{ kg}/(\text{m s})$

Mean flow velocity is an output of the model. It is controlled by the **pressure drop**, which enters the model as a volume force, e.g. for 200 Pa, sample thickness L:

$$f = \frac{200 Pa}{L}$$

Electric field enters the model as charges on fiber surfaces

---

### III. Flow: Navier-Stokes-Brinkmann equations

---

$$-\mu\Delta\vec{u} + \nabla\vec{u} \cdot \vec{u} + \kappa^{-1}\vec{u} + \nabla p = \vec{f} \text{ (momentum balance)}$$

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

$$\vec{u} = 0 \text{ on } \Gamma \text{ (no-slip on fiber surfaces)}$$

$\vec{f} = (0, 0, f)$  : force in flow(z)-direction,

$\kappa$  : porous voxel permeability,

$\vec{u}$  : velocity,

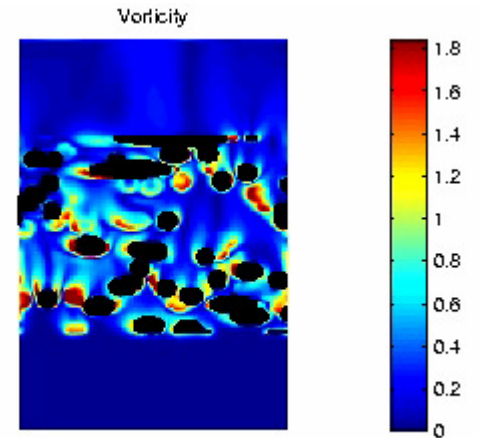
$\mu$  : fluid viscosity,

$p$  : pressure and

$\Gamma$  : fiber or deposited particle surfaces.

The flow can be solved with periodic boundary conditions if the cutout is large enough and empty space is added in front.

---



**Cross section views  
of vorticity**

### III. Electric field: Poisson equation for the potential

---

$$\Delta u = \rho \chi(\delta\Omega) : \text{Poisson equation}$$

$$\vec{E} = \nabla u : \text{Field equation}$$

$\delta\Omega$  : boundary of domain occupied by fibers (surface),

$\rho$  : source strength,

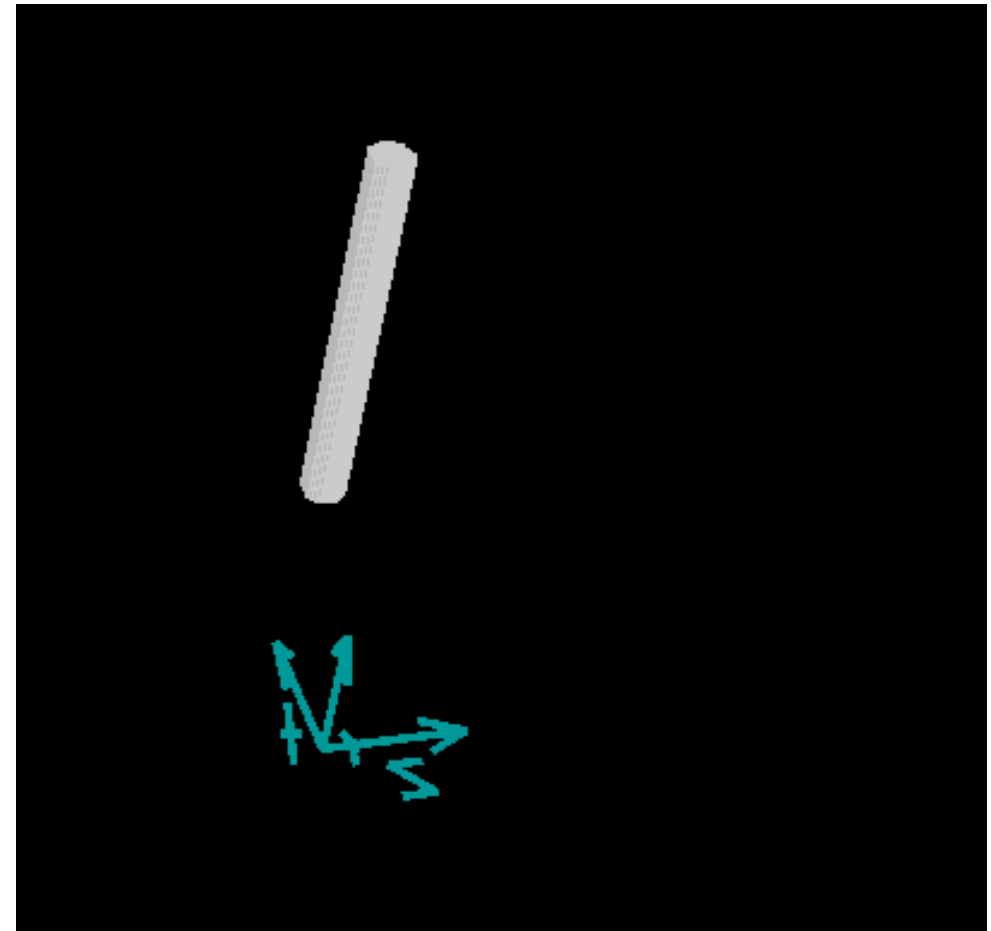
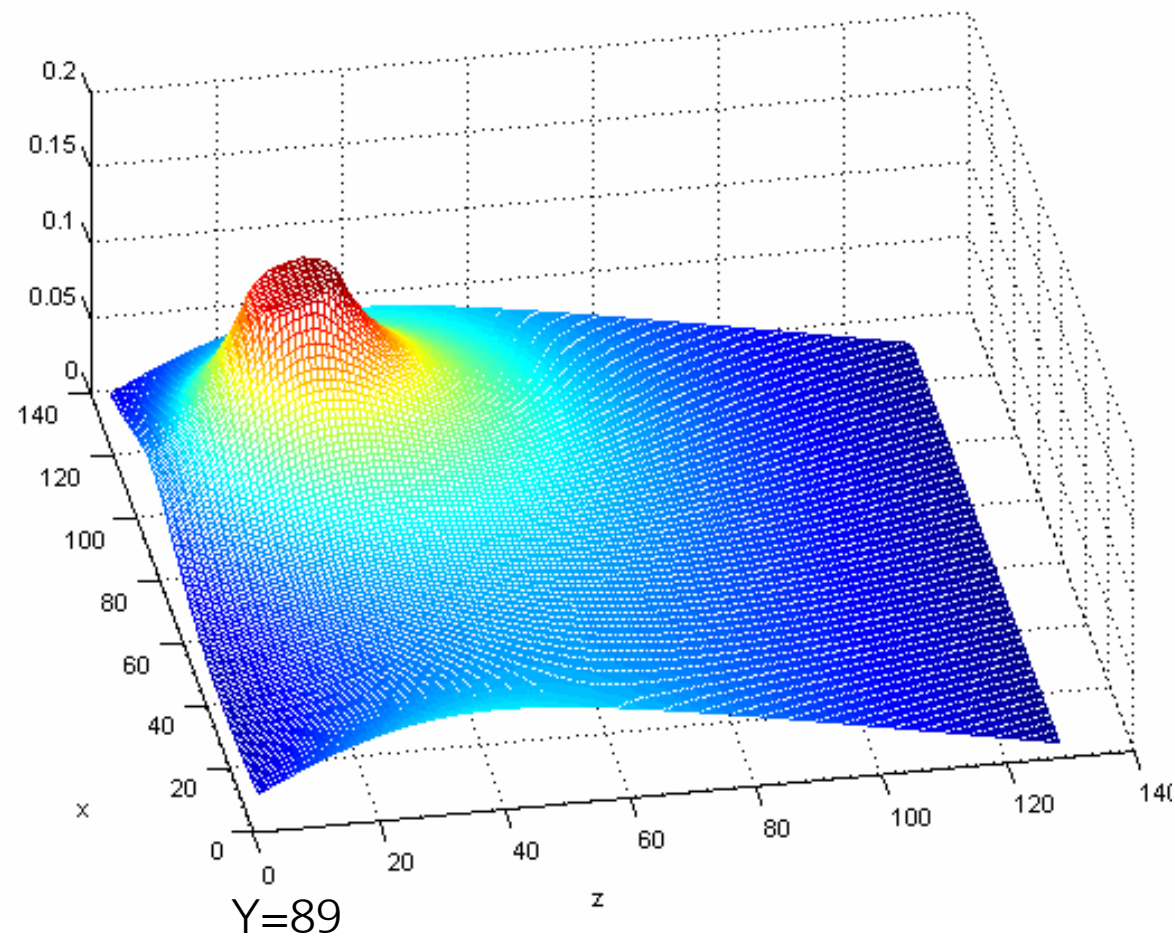
$\chi$  : surface Dirac delta function,

$u$  : the electric potential,

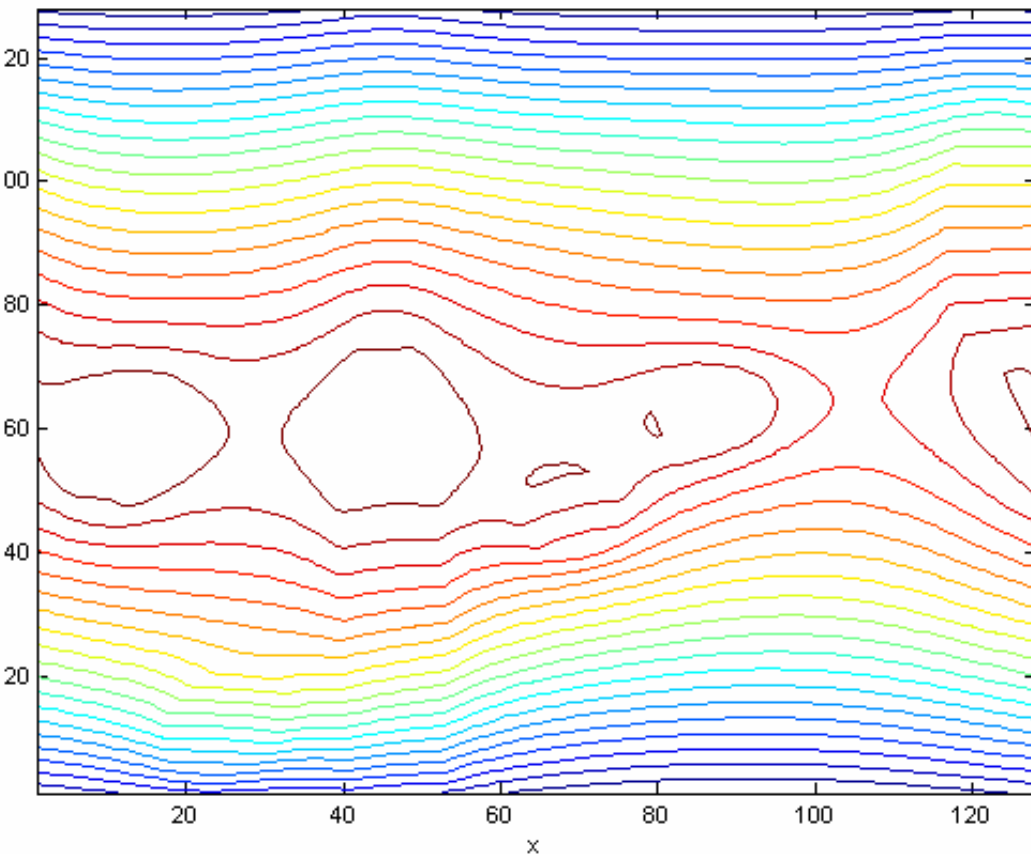
$\vec{E}$  : the electric field (the gradient of the potential).

The field can be solved with periodic boundary conditions in the lateral direction and zero potential at appropriately chosen distances outside the media.

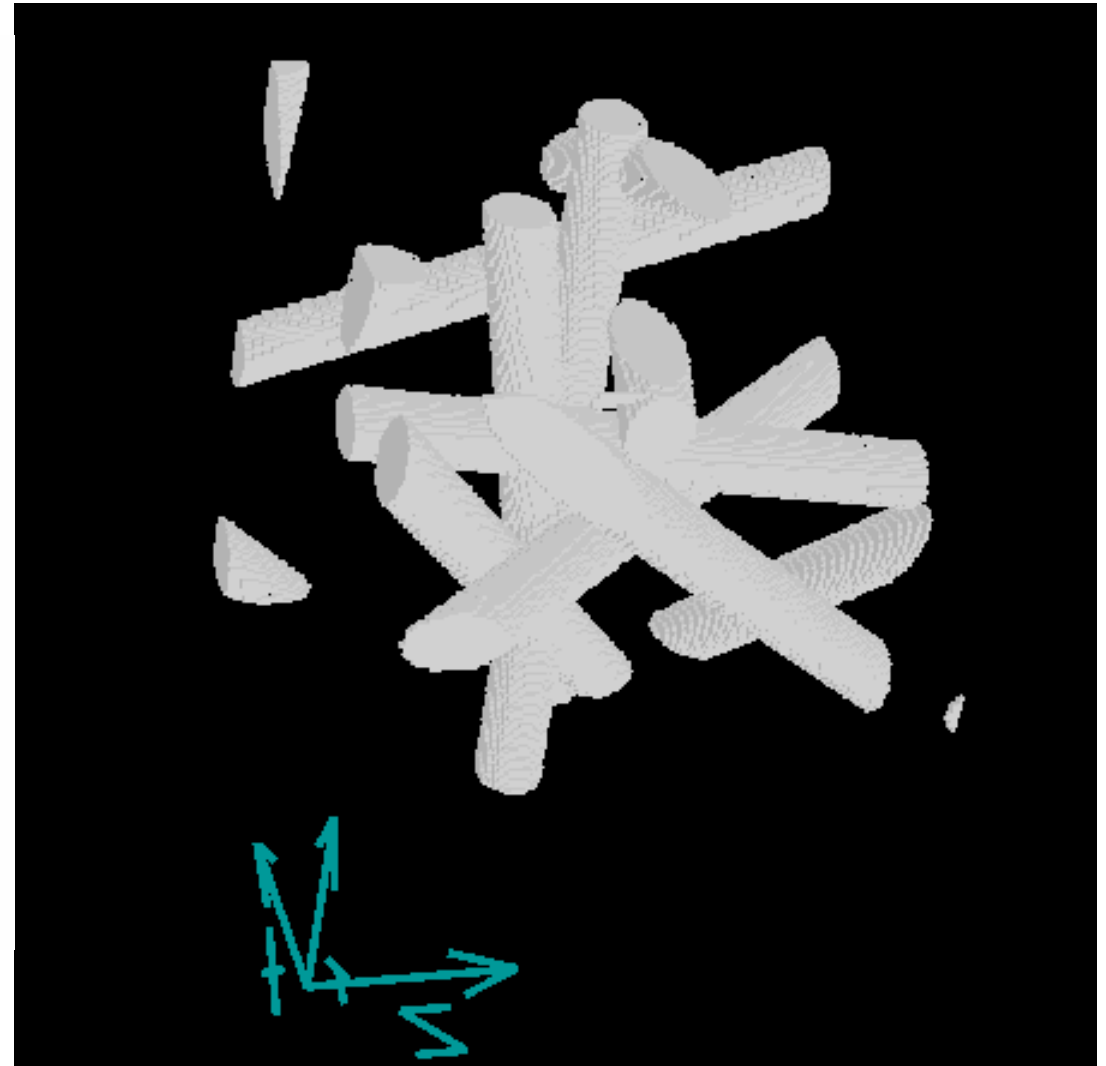
### III. Electric potential (cross section Y=89) for a single fiber



### III. Electric potential (contour $Y=89$ ) for random fibers



$Y=89$



- I. Virtual Material Design Cycle
- II. Filter Media
- III. Fluid & Electric Field
- IV. Dirt model & dirt motion**
- V. Deposition
- VI. Life time
- VII. Nano model
- VIII. Summary



## IV. Dirt Model

---

- **probability distribution of diameters of spherical particles of given material**
- **Size and material determine the particle mass**
- **Particles move with fluid via friction**
- **Particles move diffusively in fluid dependent on size and temperature**
- **Particles move electrostatically based on their own charge and the electric field**

# IV. Lagrangian description of particle motion

---

$$\frac{d\vec{v}}{dt} = -\gamma \times (\vec{v}(\vec{x}) - \vec{v}_o(\vec{x})) + \frac{Q\vec{E}_o(\vec{x})}{m} + \sigma \times \frac{d\vec{W}(t)}{dt}$$

$$\frac{d\vec{x}}{dt} = \vec{v}$$

Friction with fluid      Electric attraction      Diffusive motion

$$\gamma = 6\pi\rho\mu\frac{R}{m}$$

$$\sigma^2 = \frac{2k_B T \gamma}{m}$$

$$\langle dW_i(t), dW_j(t) \rangle = \delta_{ij} dt$$

$t$ :	time
$\vec{x}$ :	particle position
$\vec{v}$ :	particle velocity
$R$ :	particle radius
$m$ :	particle mass
$Q$ :	particle charge
$T$ :	ambient temperature
$k_B$ :	Boltzmann constant
$d\vec{W}(t)$ :	3d probability (Wiener) measure
$\vec{E}_o$ :	electric field
$\vec{v}_o$ :	fluid velocity
$\rho$ :	fluid density
$\mu$ :	fluid viscosity

- I. Virtual Material Design Cycle
- II. Filter Media
- III. Fluid & Electric Field
- IV. Dirt model & dirt motion
- V. Deposition**
- VI. Life time
- VII. Nano model
- VIII. Summary

# V. Mechanisms of filtration

Particle impact by:

A: direct interception

B: inertial impaction

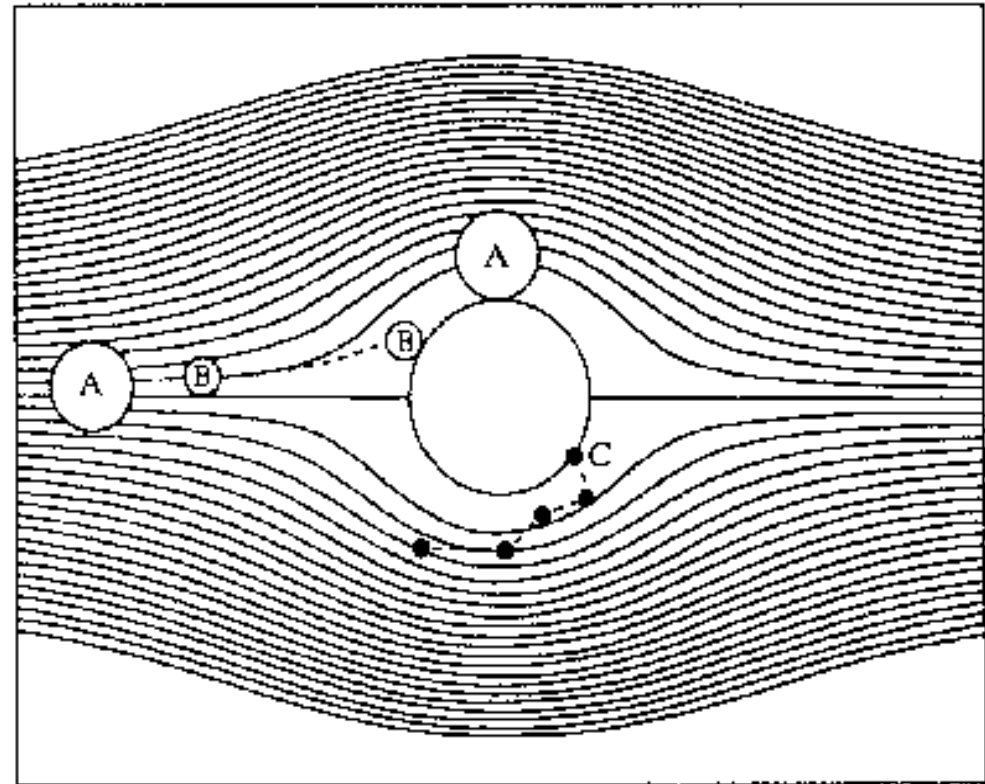
C: diffusional deposition

D: electrostatic attraction

E: sieving

F: clogging

G: other effects (gravity,...)



**Detect collisions of particles with fibers  
and previously deposited particles!**

# V. Filter Efficiency Model

---

## A) Testdust:

Sphere radii  
Specific weight  
Electrostatic charges



## B) Fluid:

Viscosity  
Density  
Temperature  
Mean flow velocity



## C) Nonwoven geometry:

Electrostatic charges  
No-slip boundary conditions



## D) Efficiency:

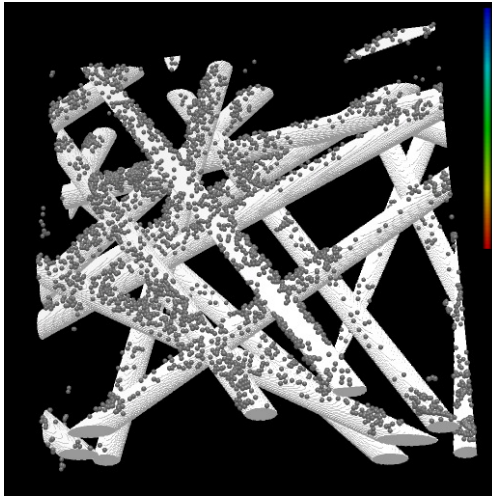
Flow & pressure drop: B & C  
Electrostatic field: C  
Friction: A & B  
Diffusion: A & B  
Collision: A & C  
Adhesion: A & C  
Electrostatic attraction: A & C  
Particle Paths: A, B & C



## E) Deposition due to: Adhesion

- Inertial impact
  - Diffusion
  - **Electrostatic attraction**
- ## Sieving

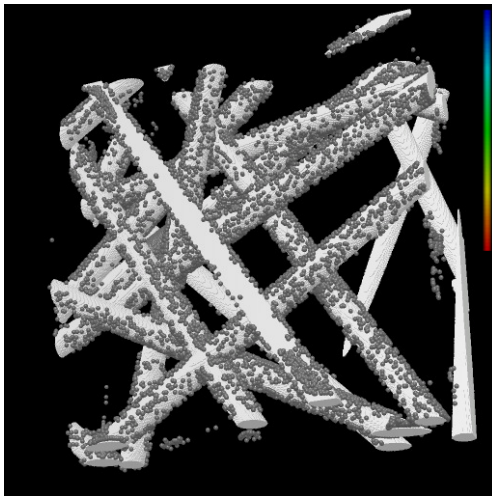
## V. Simulation results with(out) electric surface charge



Simulation result without the influence of electric surface charges on the fibers.

Front view

back view

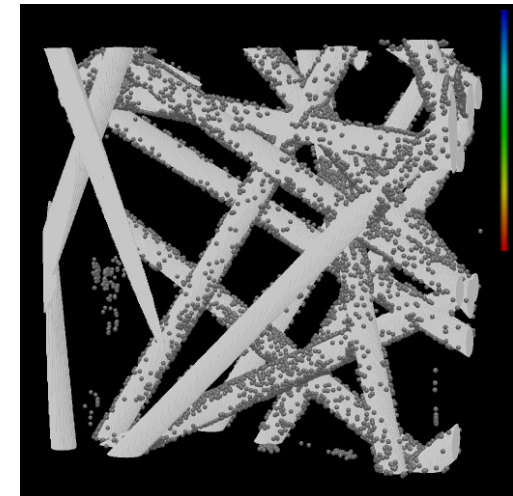


Simulation result under the influence of electric surface charges on the fibers.

Retention rate increased by about 50%!

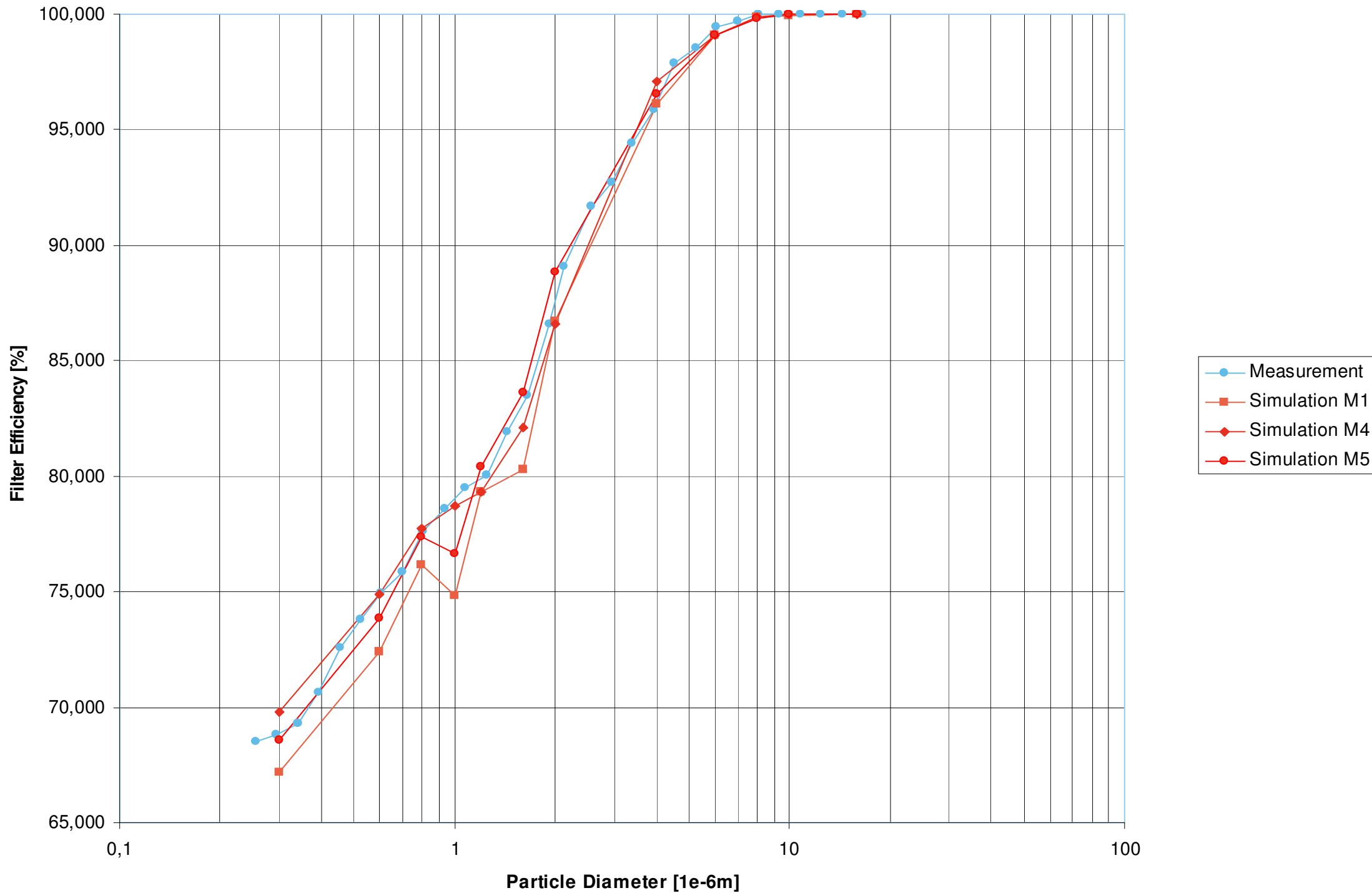
Front view

back view



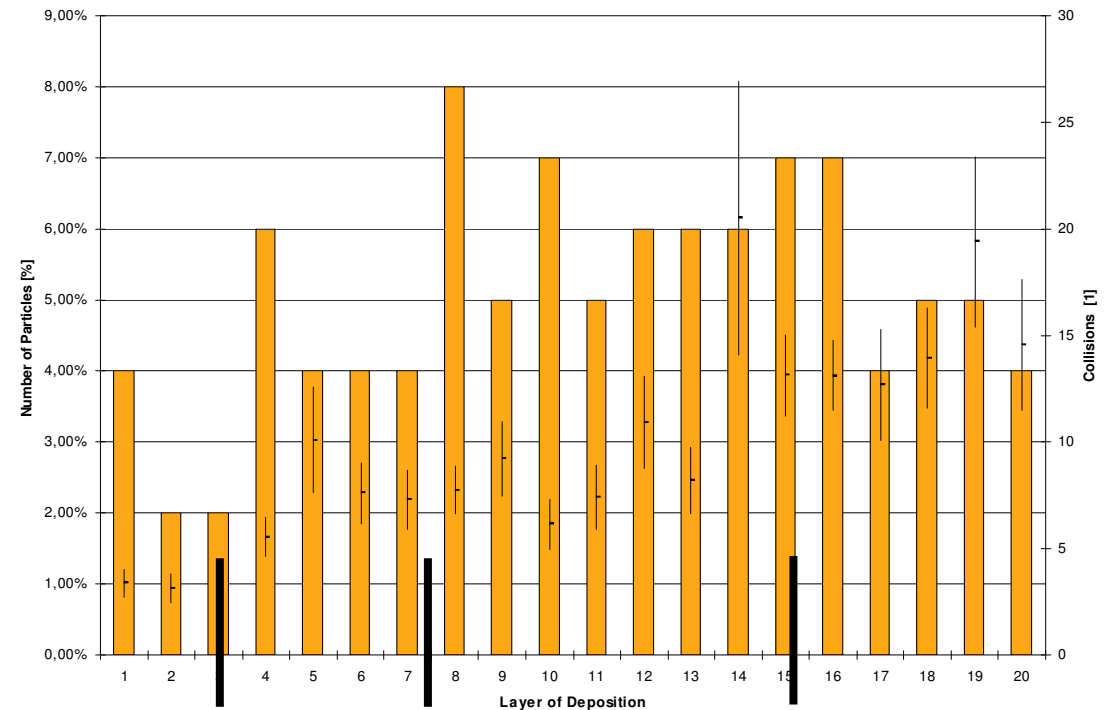


# Filter Efficiency



# V. Deposition Diagram

- Deposition locations are 20 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 of gradient material indicated by thick black lines:



Inlet



- I. Virtual Material Design Cycle
- II. Filter Media
- III. Fluid & Electric Field
- IV. Dirt model & dirt motion
- V. Deposition
- VI. Life time**
- VII. Nano model
- VIII. Summary

## VI. Decoupling of fluid flow and particle motion simulations

---

Assume particle density is very low, then:

- Particles move and deposit independently, they do not collide in the air.
- When many particles have deposited, the fluid flow is significantly altered.
- So, for clogging, the volume image is periodically updated by deposited particles and the flow field in this volume image is recomputed.
- Subsequent particle motion is computed based on the updated flow field, particle deposition is based on the updated volume image.

# VI. Filter Life Time Model

## A) Testdust:

Sphere radii  
Specific weight  
Electrostatic charges

## B) Fluid:

Viscosity  
Density  
Temperature  
Mean flow velocity

## C) Nonwoven geometry:

Electrostatic charges  
No-slip boundary conditions

## D) Efficiency:

Flow & pressure drop: B & C  
Electrostatic field: C  
Friction: A & B  
Diffusion: A & B  
Collision: A & C  
Adhesion: A & C  
Electrostatic attraction: A & C  
Particle Paths: A, B & C

## E) Deposition due to: Adhesion

- Inertial impact
- Diffusion
- Electrostatic attraction

## Sieving

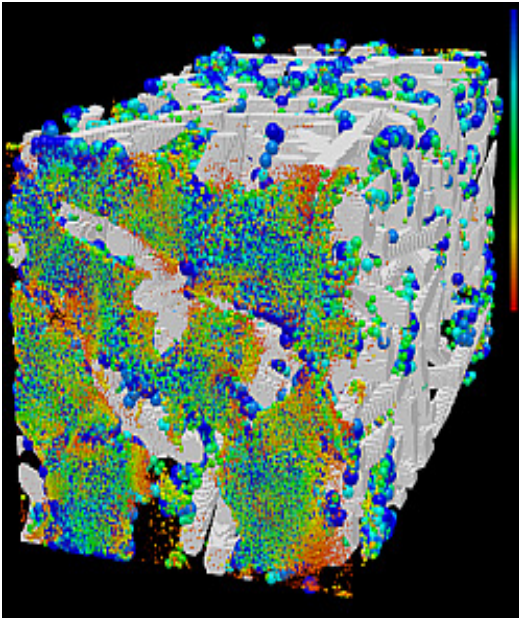
## G) Multipass:

Unfiltered particles change  
particle size distribution

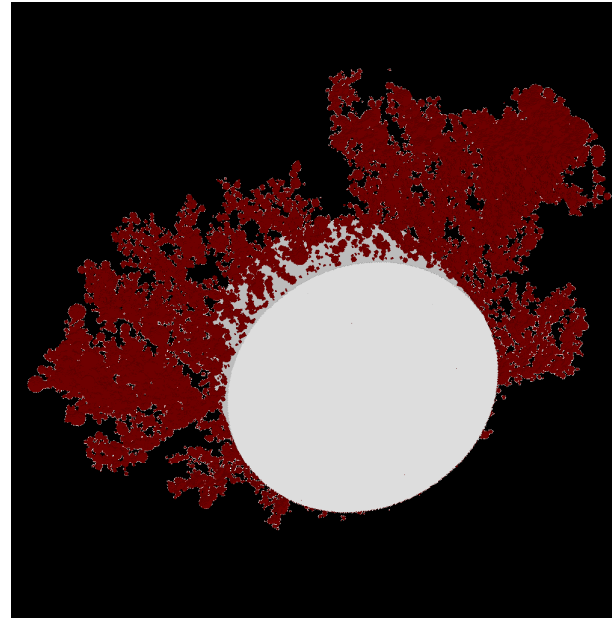
## F) Clogging:

Deposited particles determine  
new geometry model, including  
**permeable** voxels

## VI. Clogging of nonwoven & ceramic; dendrites on single fiber



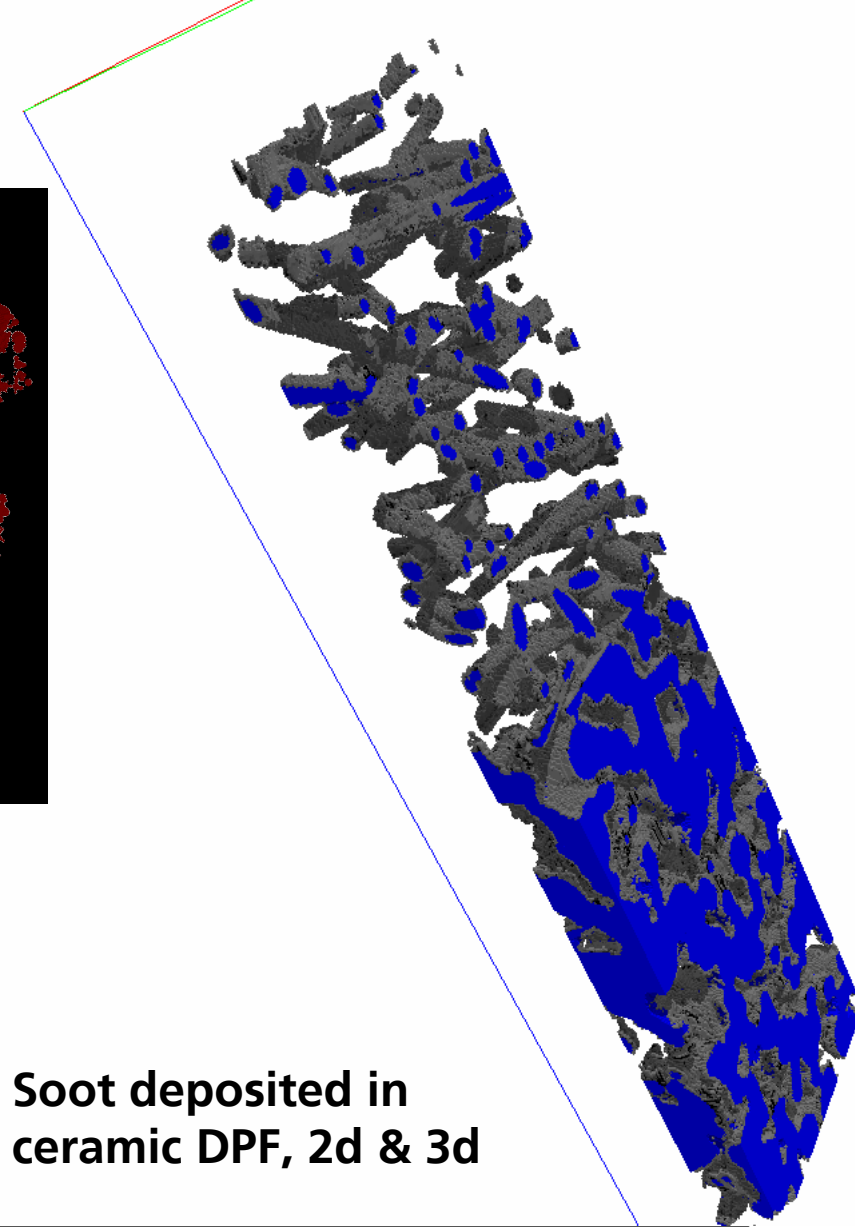
Clogged nonwoven



Soot deposition on  
a single fiber

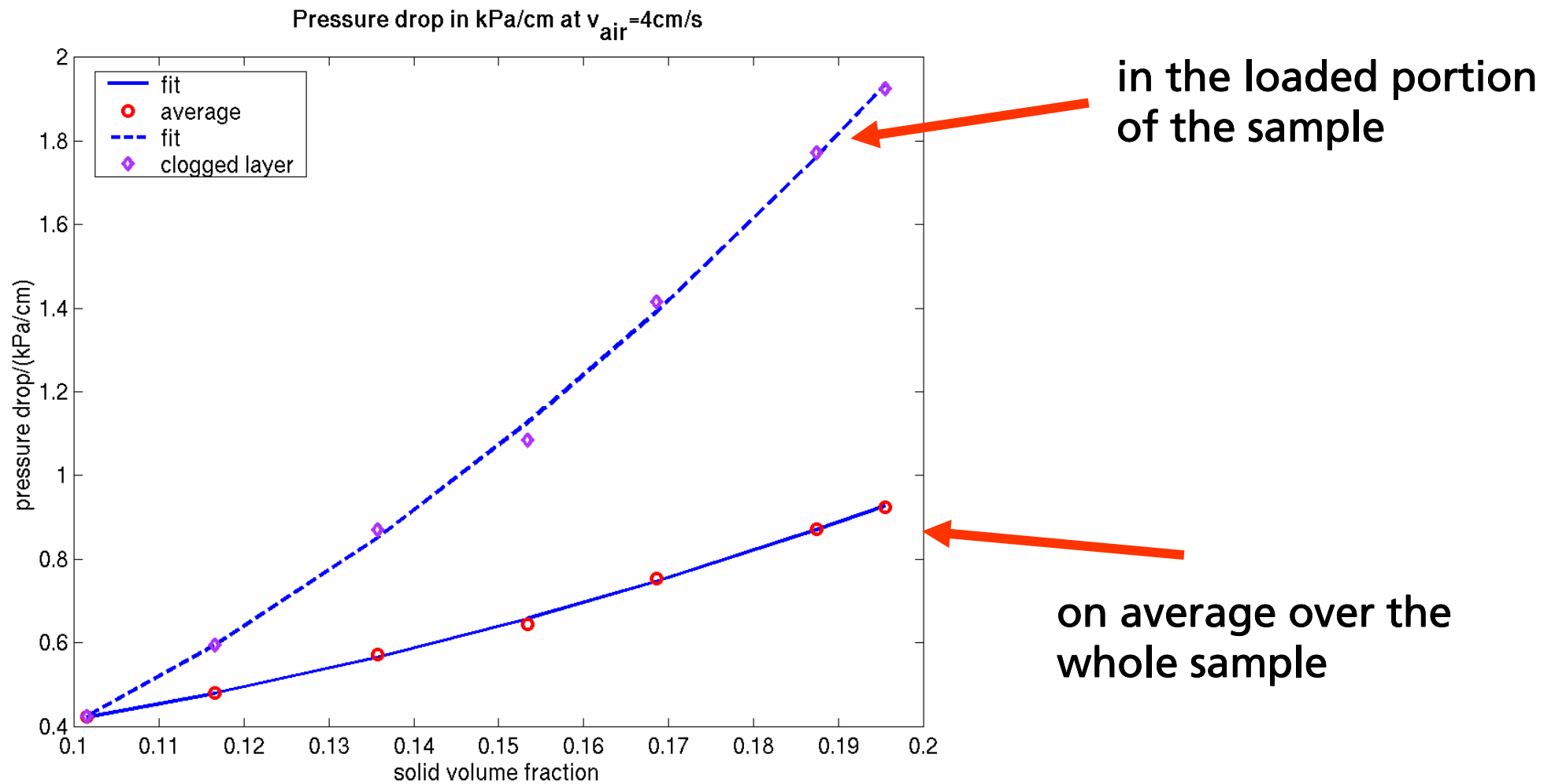
Deposition occurs on fibers and  
on previously deposited particles

Soot deposited in  
ceramic DPF, 2d & 3d





## VI. Time Dependent Pressure Drop



**I. Virtual Material Design Cycle**

**II. Filter Media**

**III. Fluid & Electric Field**

**IV. Dirt model & dirt motion**

**V. Deposition**

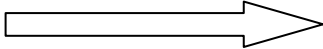
**VI. Life time**

**VII. Nano model**

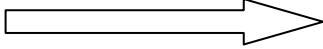
**VIII. Summary**

# VIII. Summary

---

Complex geometry of real textiles  high resolution volume image

"Slow" flow  Stokes equations

Highly diluted  Particles do not modify fields

Material & Dirt models

Fluid & electric models

Deposition & Clogging models

Output are models, predicted filter properties, and optimized material geometries

Models & equations are fairly standard. Completeness of approach is new.

Difficulties: knowledge of parameter settings, high resolution for large cutouts.

Goals: "generic agreement with reality", little need for recalibration for new application areas. **New material must be manufactured and predictions must be verified.**