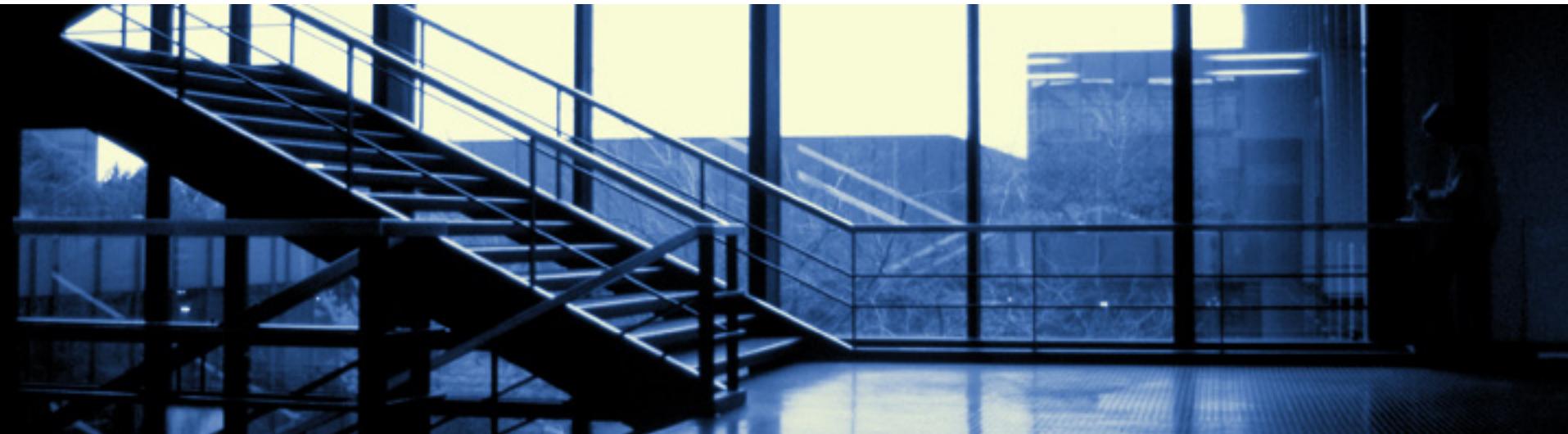


# Numerical and Experimental Investigation of the Plasma Down Stream Reactor

Master Thesis

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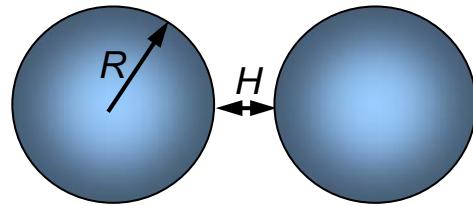


# Project Background

- Cohesive powders cause many problems in the chemical & pharmaceutical industry
  - Conveyance
  - Mixing
  - Bottling
- Reason: Interparticle forces
- We **improve the flow behavior of cohesive powders** by reducing these forces

# Principle: Nanoparticle Deposition

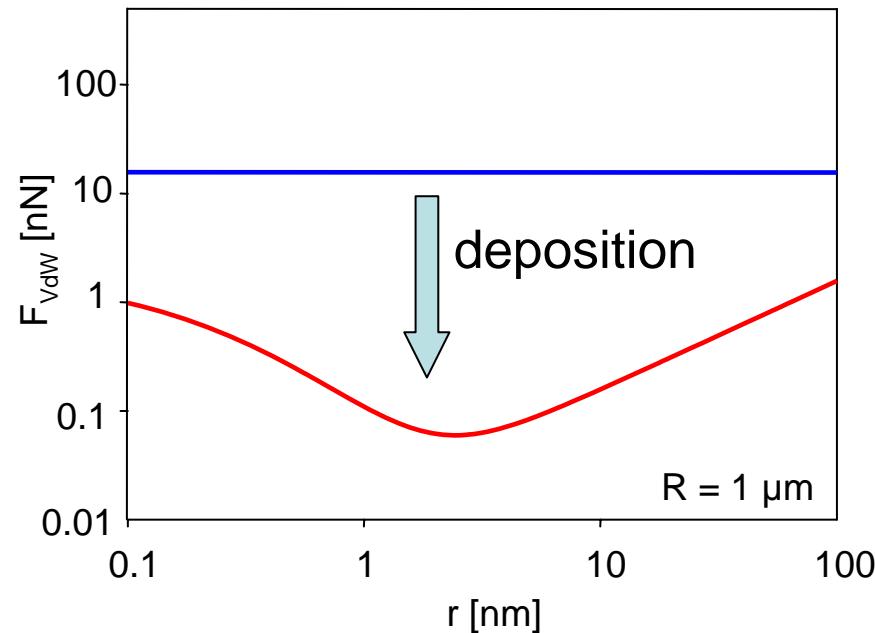
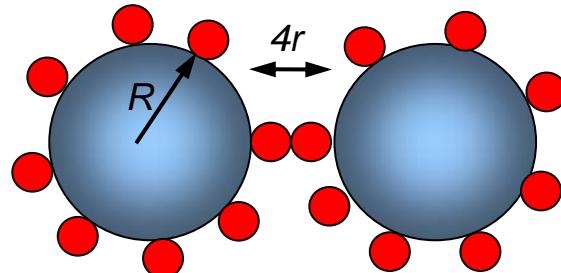
- Van der Waals Force according Hamaker



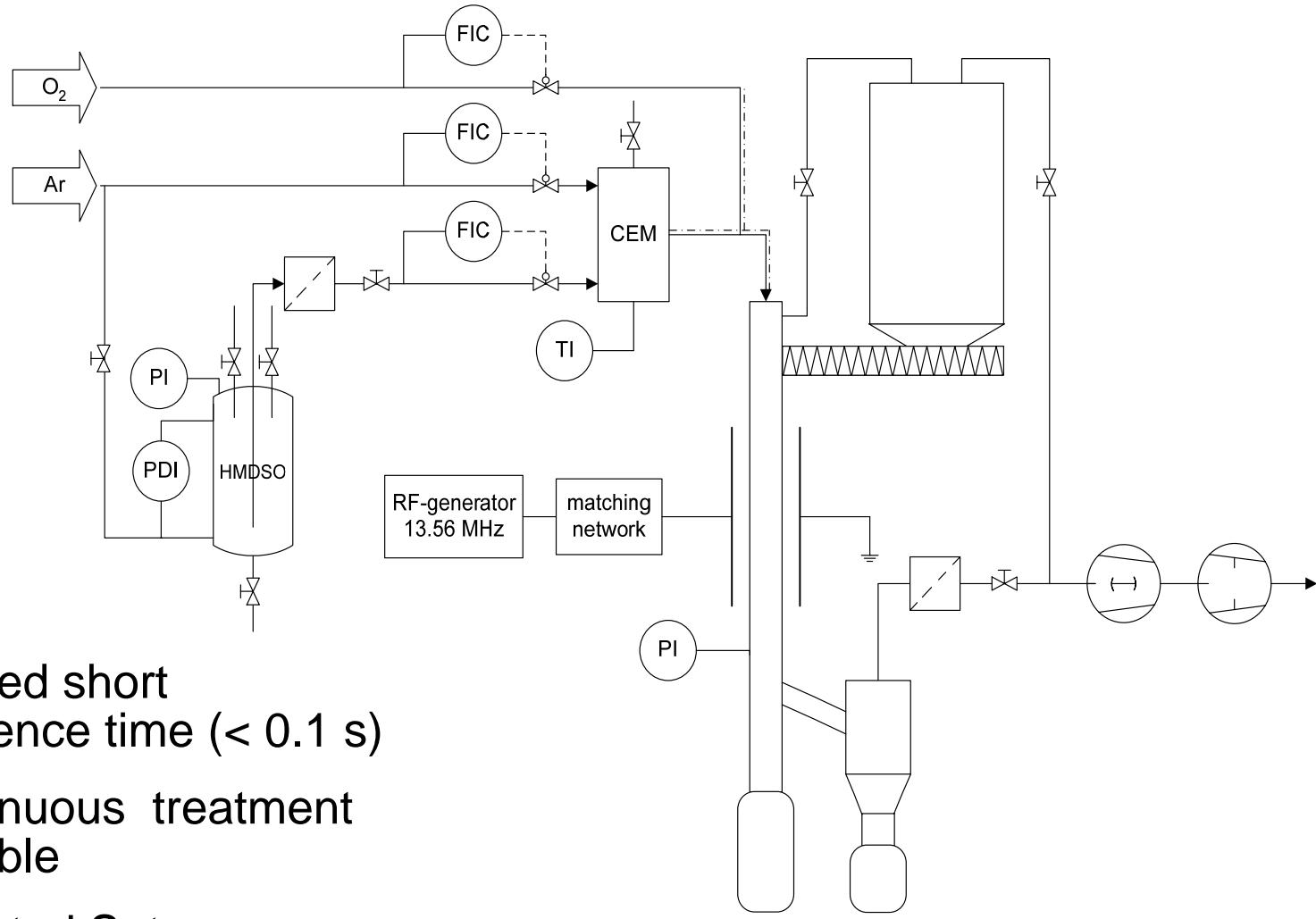
$$F_{VdW} = \frac{A}{12} \cdot \frac{R}{H^2}$$

$$H_{min} = 4 \cdot 10^{-10} \text{ m}$$
$$A = 3 \cdot 10^{-20} \text{ J}$$

- Increasing the distance between the particles by a surface deposition



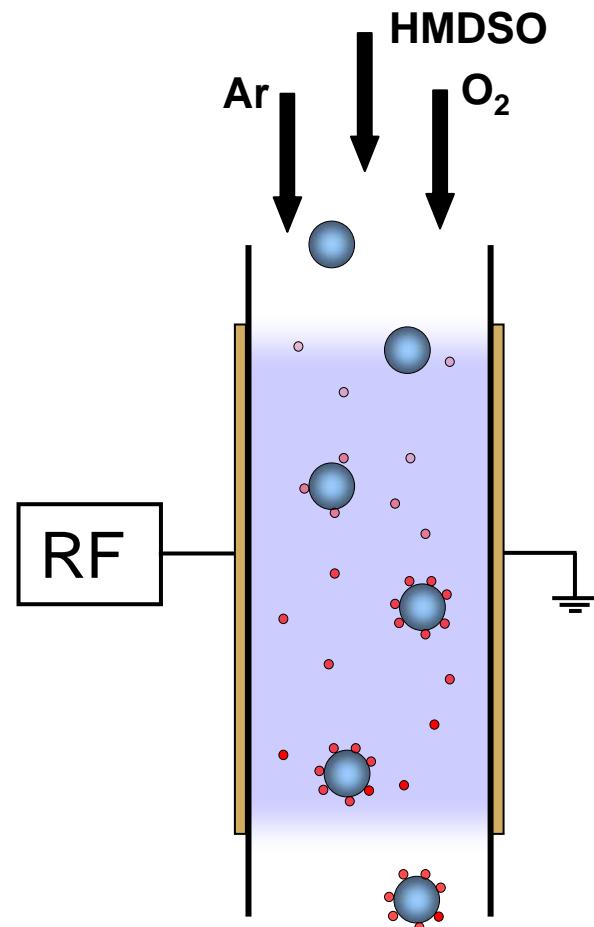
# Plasma Down Stream Reactor



- Defined short residence time (< 0.1 s)
- Continuous treatment possible
- Patented Setup

# Nanoparticle Deposition in the Plasma

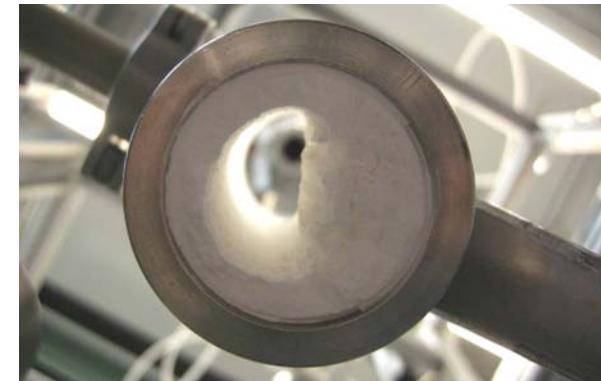
- Process to build  $\text{SiO}_x$  Nanostructure on the substrate particle surface



# Motivation for the Master Thesis

Adhesion at the walls

- Problem:



Chemical degradation or melting of temperature sensitive particles

Blockage of the reactor  
→ no continuous operation

- Implications:

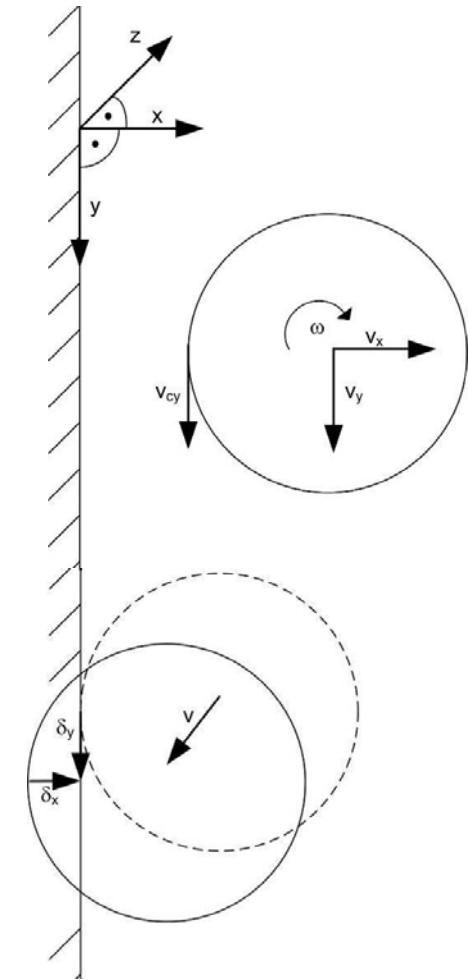
Investigation of the:  
— heat fluxes  
— temperature profile  
— particle temperature

Numerical model of the particle-wall interaction  
→ Avoid adhesion

- Goals:

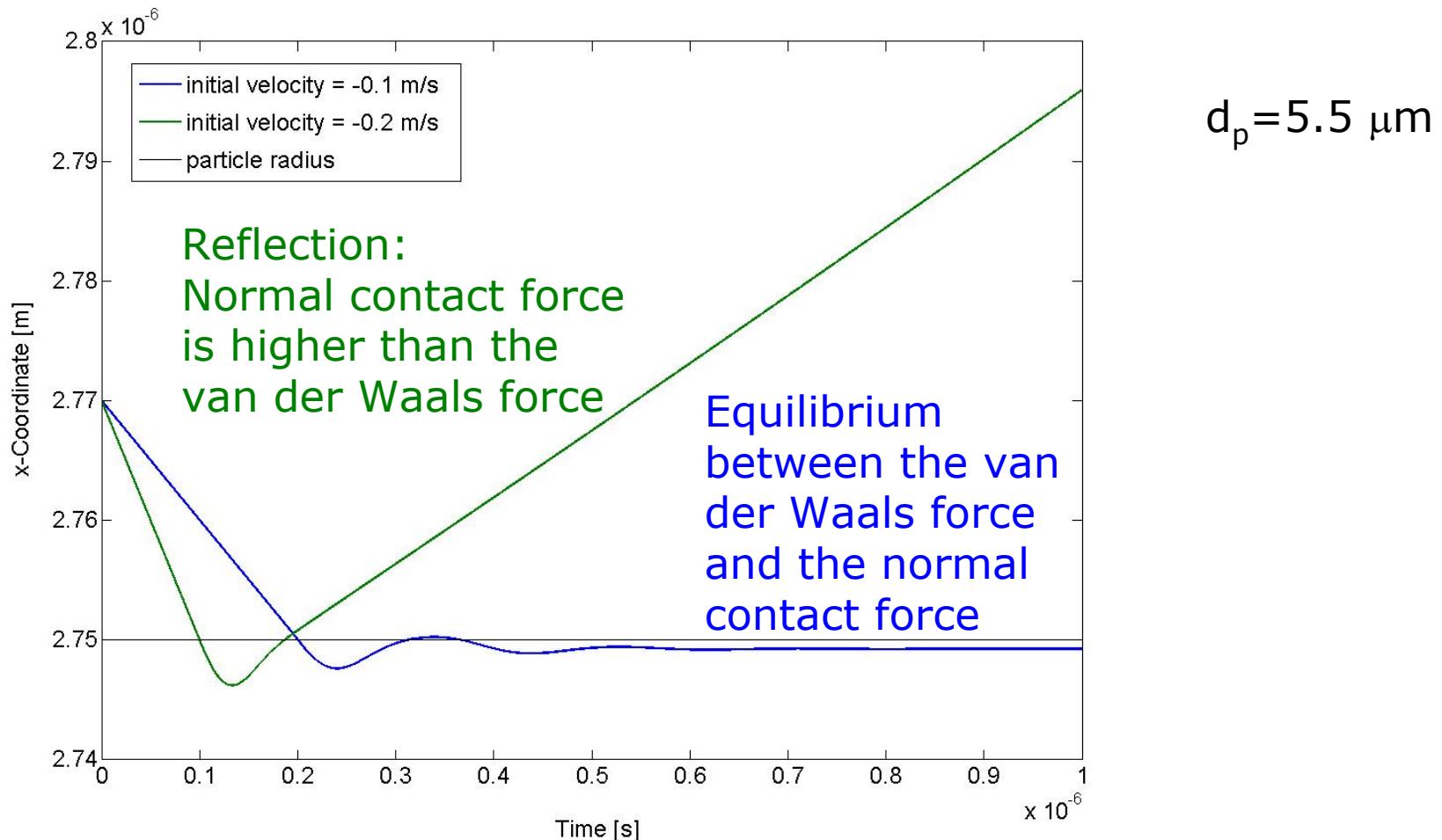
# Numerical Model Definition

- 2D model
- Particle-wall interaction
  - Contact & Damping forces
  - Van der Waals force
- Particle path without contact
  - Coulomb force
  - Fluid drag force
  - Ion drag force
- Qualitative statements



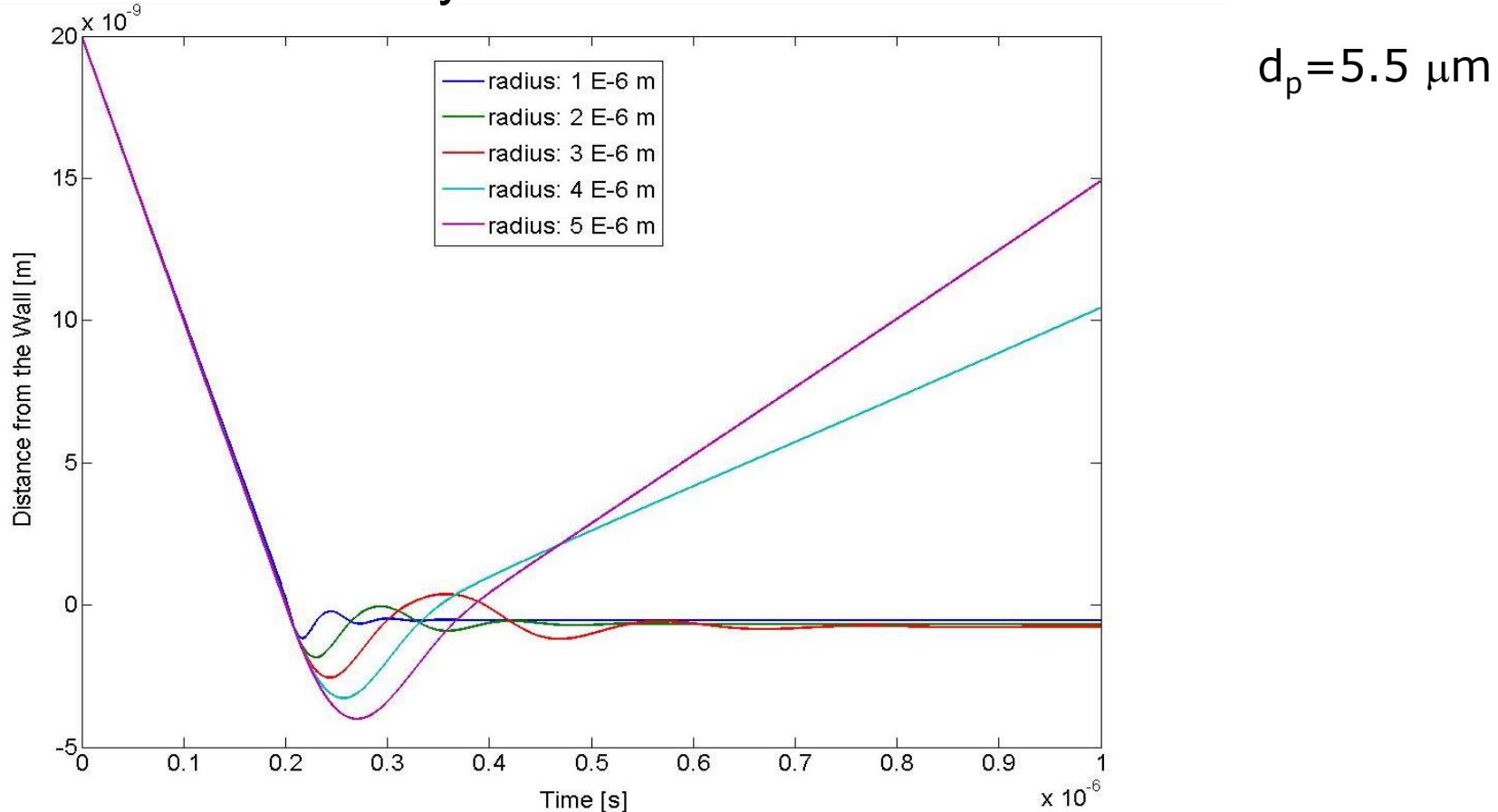
# Particle-Wall Contact

- Adhesion depends on the normal velocity



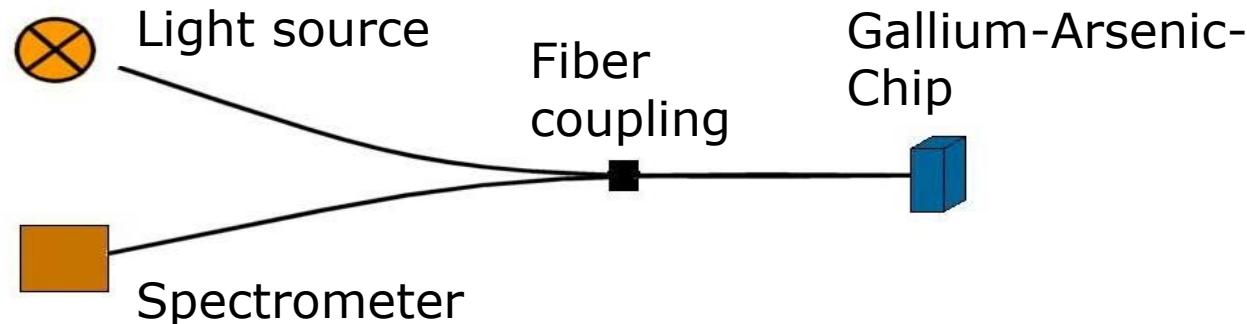
# Particle-Wall Contact

- Dependency on the particle radius
  - normal velocity: 0.1 m/s



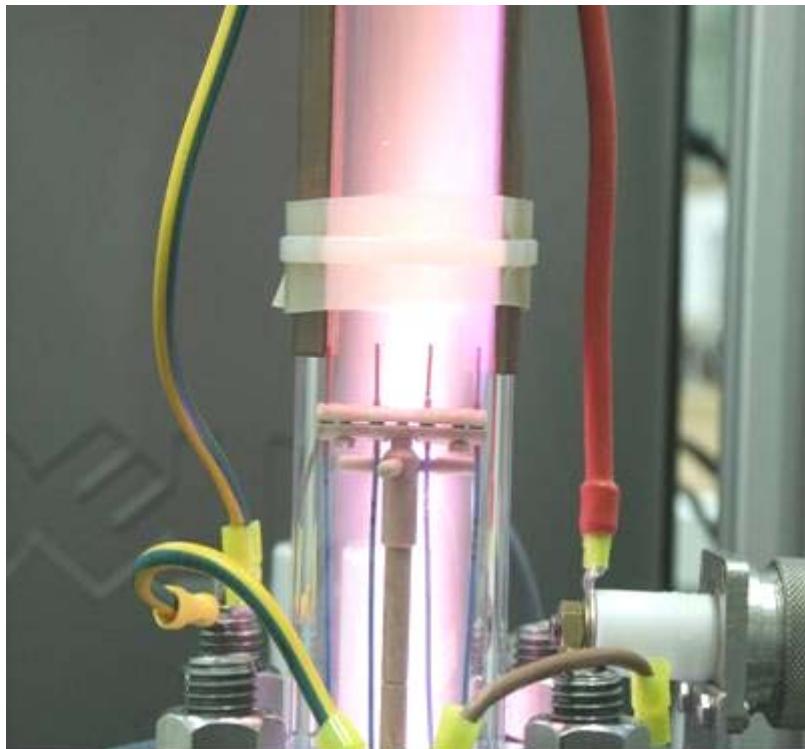
# Temperature Measurements

- Gas and wall temperature in the plasma zone
- Fiber-optic system
  - GaAs crystal with temperature dependent band gap displacement

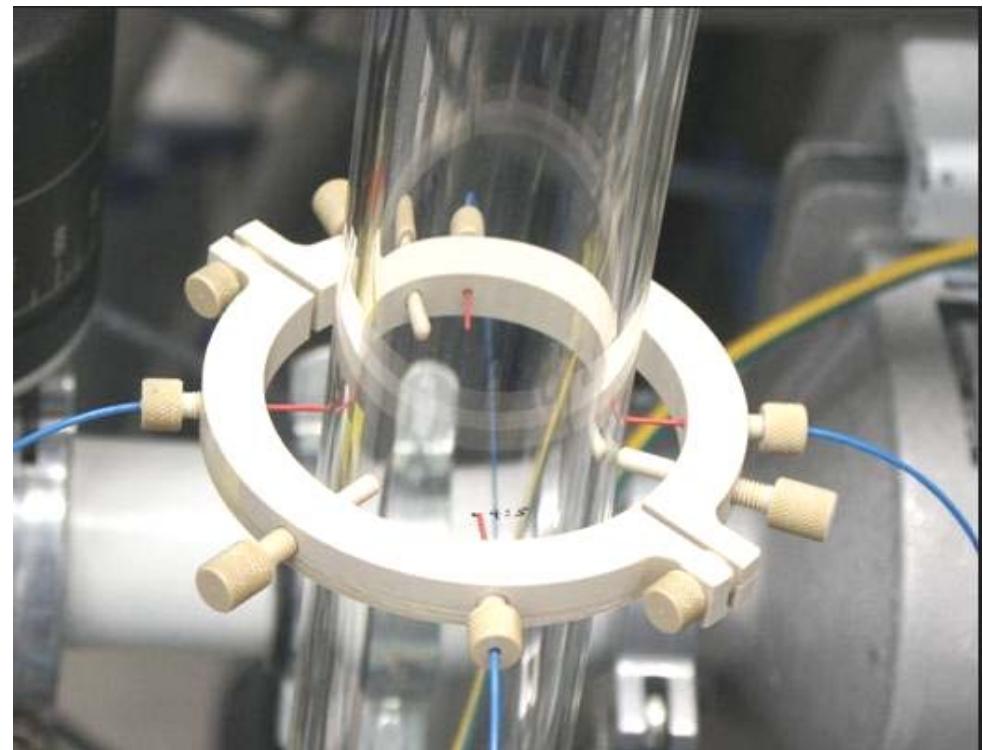


- Not influenced by electromagnetic fields

# Sensor fixation



Inside the reactor



Outside wall

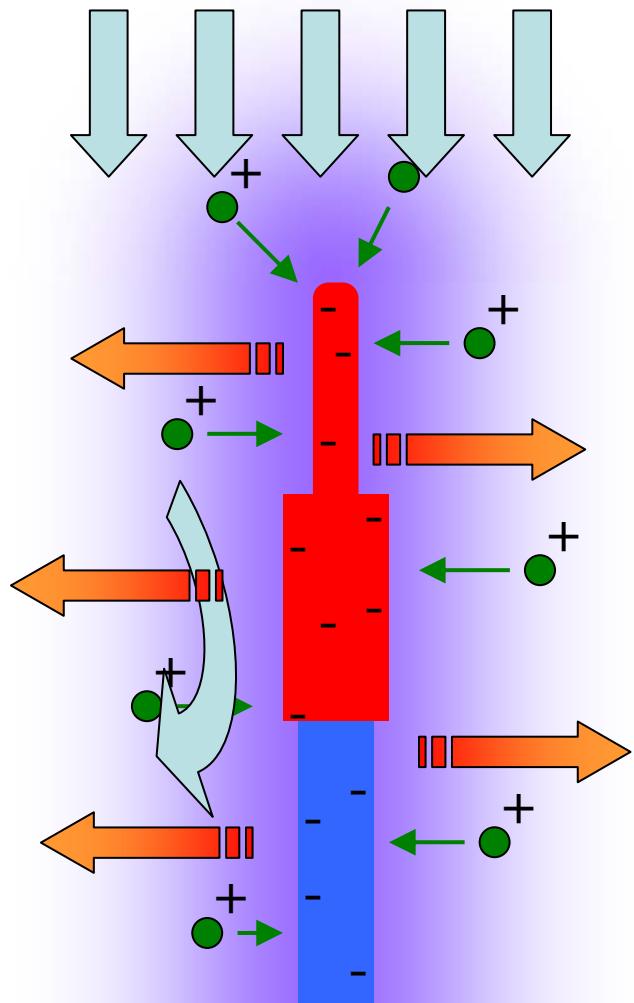
# Temperatures in the Plasma

Heating due to ion bombardment

Loss due to radiation

Loss due to convection

→ No direct measurement possible



# Calculation Procedure

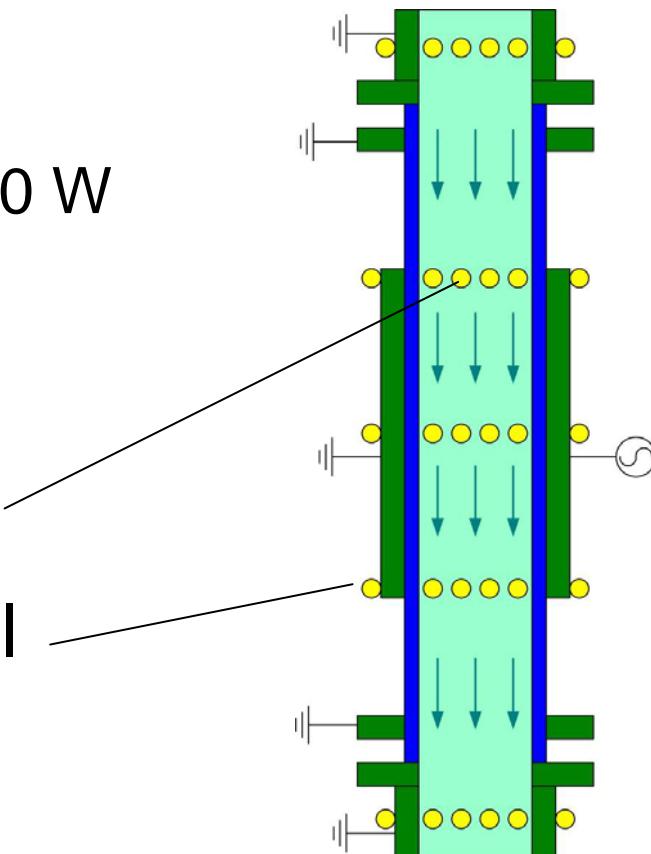
- Sensor temperature measurements
- Calculation of the heat fluxes

$$\frac{dT_S}{dt} \cdot \frac{m_s \cdot c_{p,S}}{A_s} = \alpha (T_g - T_s) + \dot{Q}_{plasma}'' - C_s \cdot \varepsilon_s (T_s^4 - T_{w,in}^4)$$

- Heating due to the plasma
- Radiation
- Convection
- Calculation of the resulting particle temperature

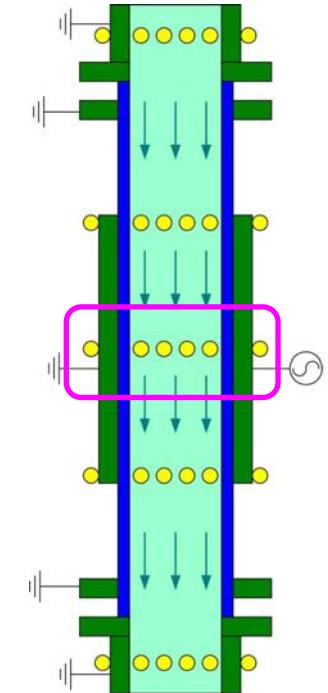
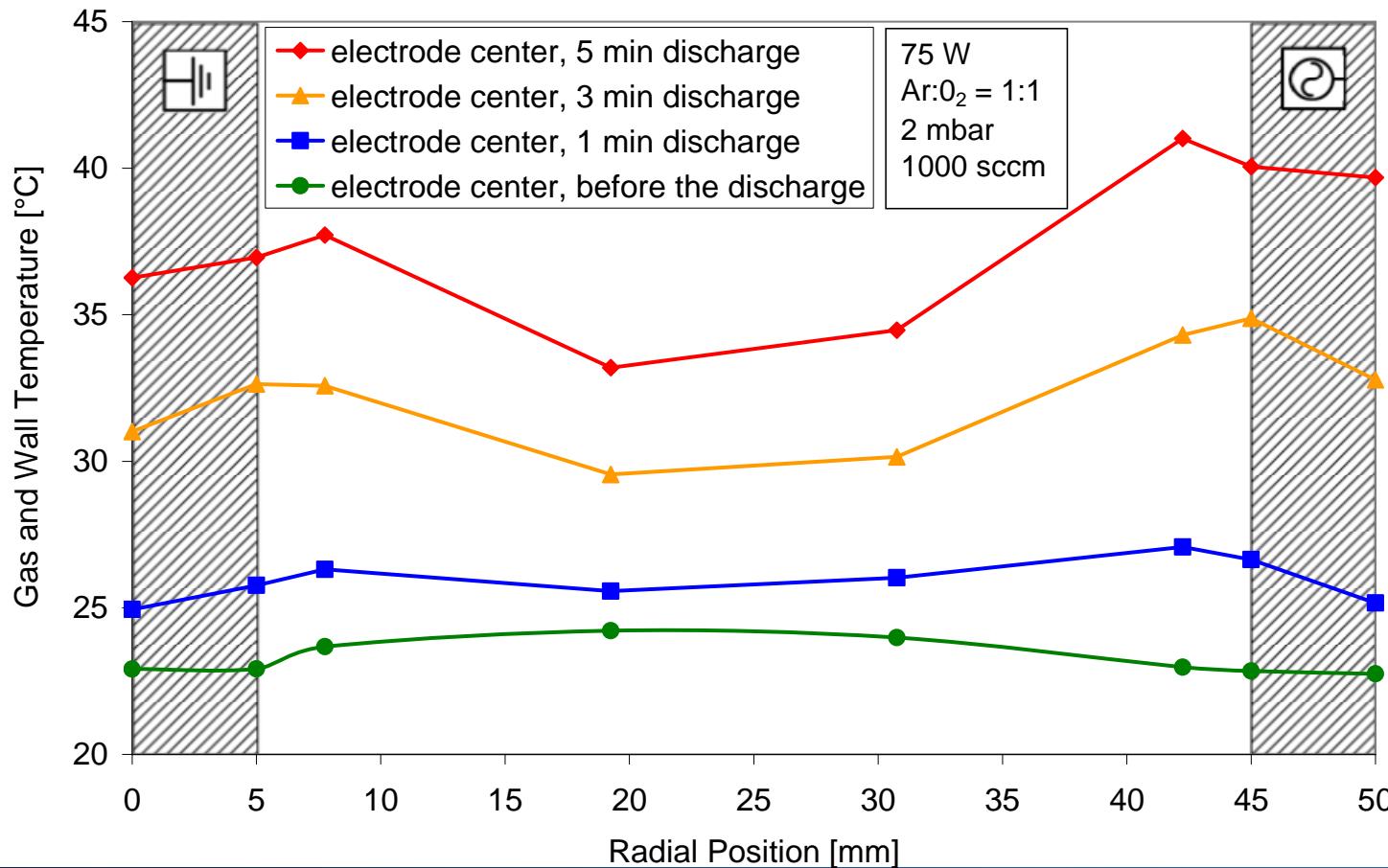
# Parameter Study in the Short Reactor

- Influence on the temperature propagation
  - Plasma forward power: 50, 75, 100 W
  - Pressure: 1.5, 2, 3 mbar
  - Ar:O<sub>2</sub> ratio: 1:3, 1:1, 3:1
- 4 radial positions in the reactor
- 4 tangential positions at the wall
- 5 heights



# Gas and Wall Temperatures

- Maximum near the wall
- Increasing with time

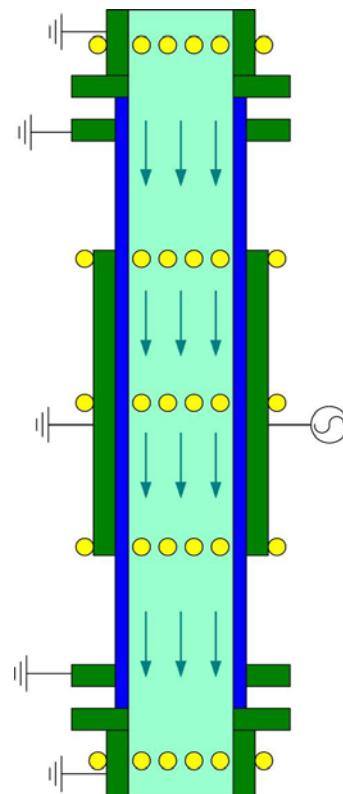
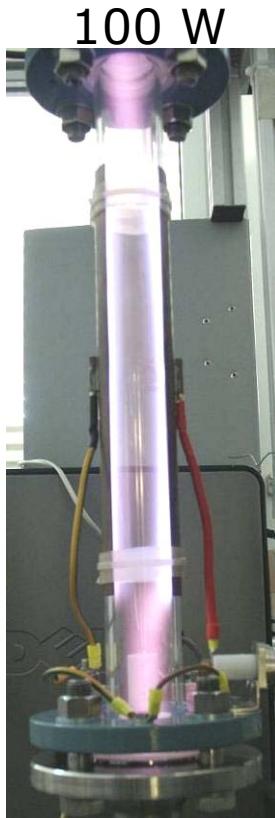


# Results from the Parameter Study

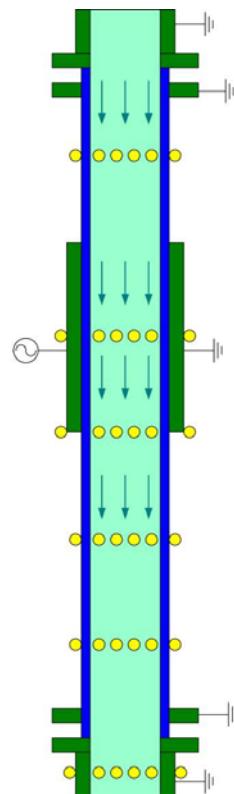
- Higher plasma forward power
  - Higher heat flux due to the plasma
  - Higher gas temperatures
  - Expansion of the plasma zone
- Higher pressure
  - Contraction of the plasma zone
- Gas composition
  - No main effect in the investigated range

# Discharge into the Lower Flange

- Lower flange acts as second grounded electrode  
→ Second “Hot Spot” beside the main electrodes

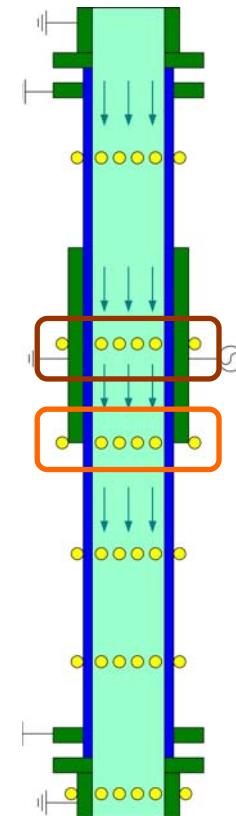
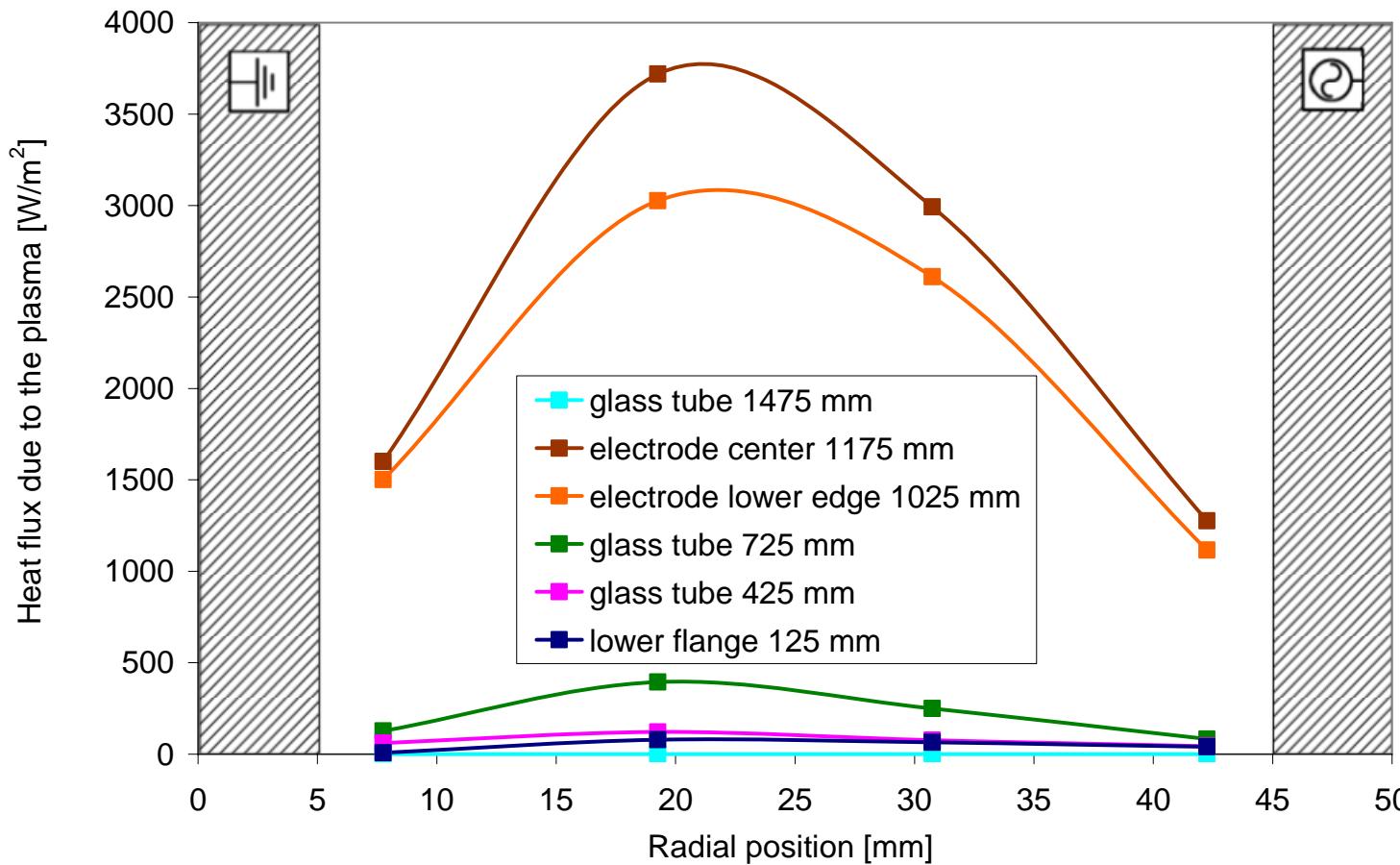


Change of the setup:  
Longer glass tube  
1.5 m instead of 0.5 m



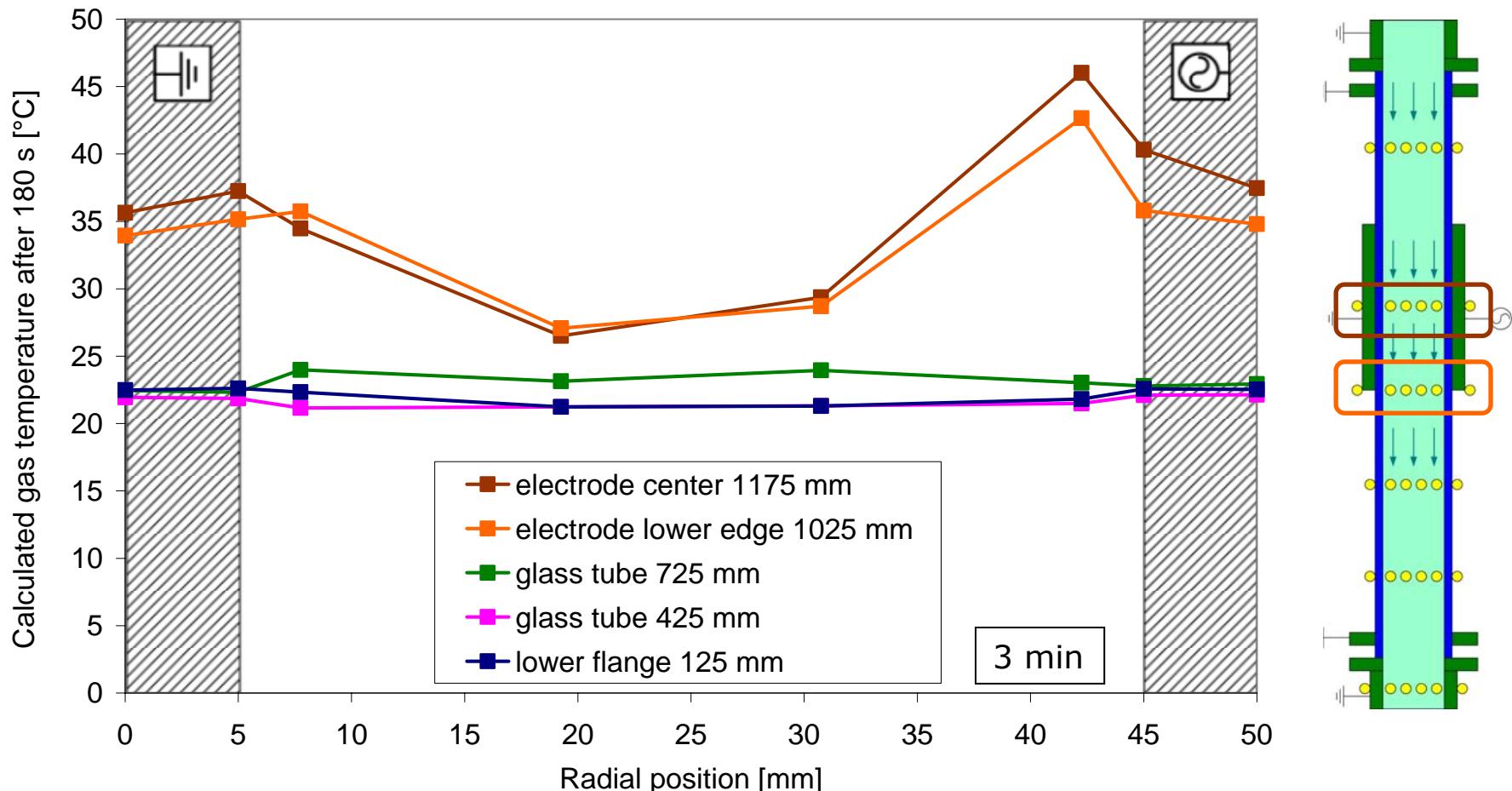
# Plasma Heating: Spatial Distribution

- No heat flux due to the plasma in the flanges  
→ Plasma zone is confined in the glass cylinder!

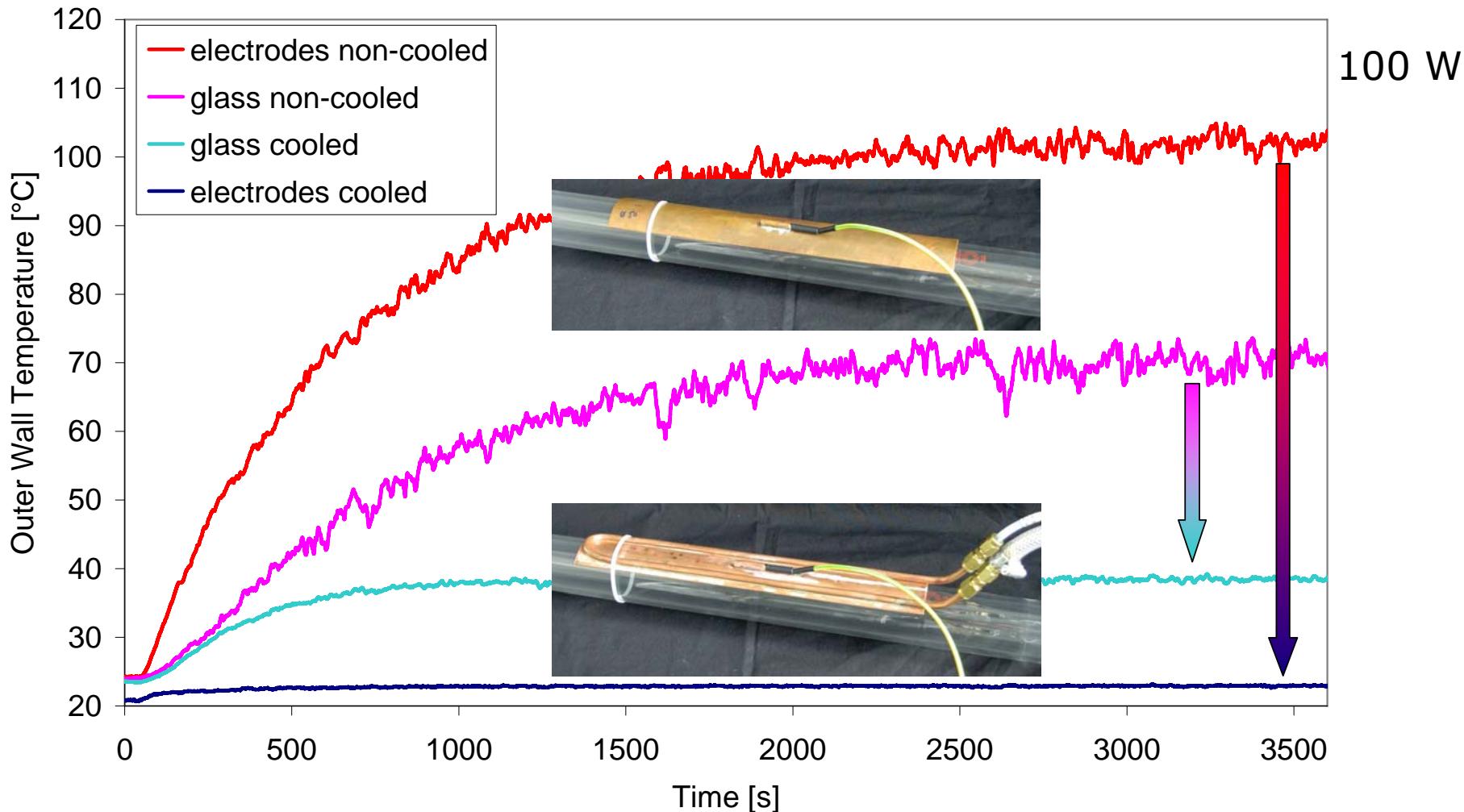


# Gas Temperature: Spatial Distribution

- Only high gas temperatures in between the electrodes



# Effect of Electrode Cooling



# Maximal Particle Temperature Calculation

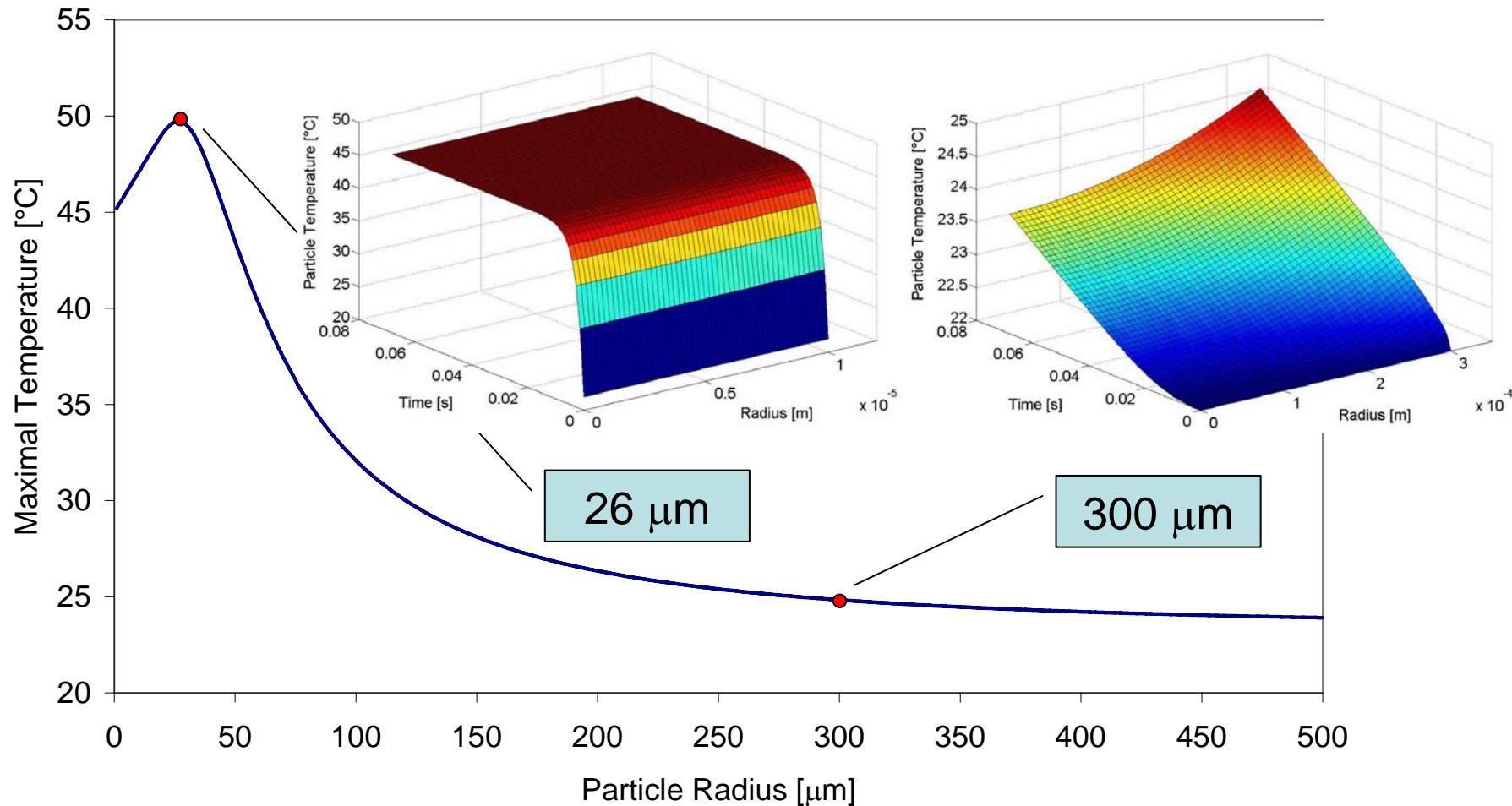
- Applying the different heat fluxes to a particle
- Typical residence time: 0.068 s
- Electrode cooling, short time operation, no adhesion at the wall:
  - Mean inner wall temperature: 40 °C
  - Mean gas temperature: 45 °C
  - Heat flux due to the plasma: 5000 W/m<sup>2</sup>



$$T_{p,\max} = 50 \text{ °C}$$

# Particle Temperature

- Dependency on the particle size



# Conclusion

- Numerical model
  - particle wall interaction
  - dominant forces
- Parameter study in the original reactor
  - position, power, pressure and gas composition
- Long reactor
  - confinement of the plasma
  - electrode cooling unit
- Particle temperature