Investigation of dust devil-like vortices in a large-scale laboratory experiment using particle tracking velocimetry

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Youtube: Dust Devil Oregon, USA

Dust Devils – A Definition

sturmarchiv.ch

luftbild-blossey.de

sciencemag.org

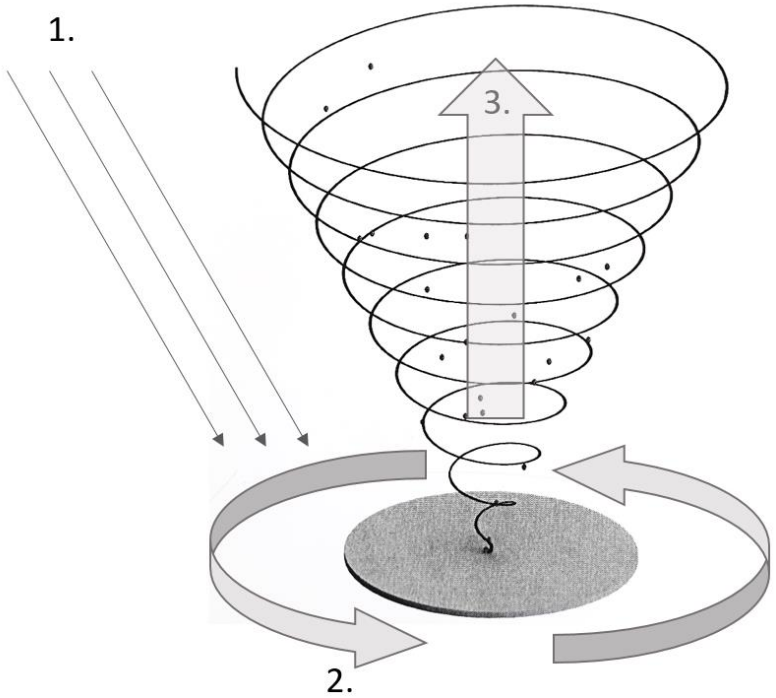
Dust Devils are organized convective vortices with vertical axes which are made visible by entrained dust or other particles.

Dust Devils – A Definition

- **How dust devils form:**

1. Sun heats up the ground (Genesis during strong insolation)
2. Warm air begins to rise, creating area of low pressure over the hotspot
3. Air rushes in and swirling air picks up
4. Dirt creating a dust devil

- Properties: Core with minimum in pressure and maximum in vertical vorticity (vorticity = curl of the flow velocity vector)



Motivation

Experimental investigation with in situ measurements are very difficult to perform

We want to present how dust devils can be investigated in a well-defined laboratory experiment

Requirements for model experiment:

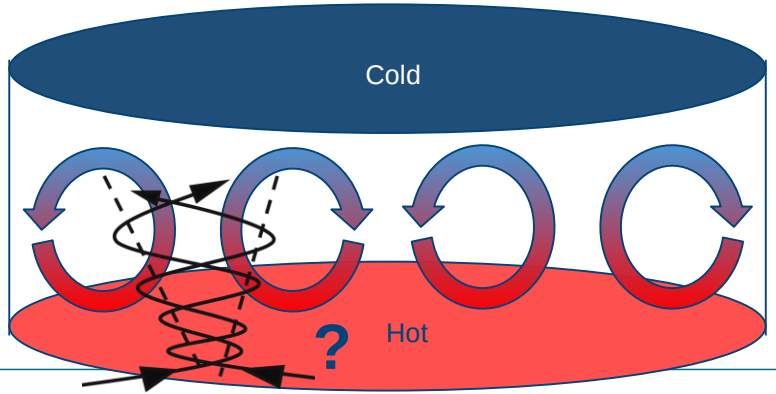
- Controlled conditions (reproducibility)
- Large temperature gradient against the gravitational vector to produce the buoyancy forces, they are characterized by a dimensionless number, the so-called Rayleigh-number:

$$Ra = \frac{\beta g \Delta T H^3}{\nu \kappa}$$

- Lateral extent of the model experiment is greater than the horizontal one (as in the atmosphere) so that more than one convection role exist, because from LES studies it is known that dust devils arise in these areas, where an uplift between the individual convection cells is located:

Aspect Ratio: $\Gamma = \frac{D}{H} > 1$

β – thermal expansion coefficient
g – gravitational acceleration
ΔT – temperatur difference
H – vertical extent
ν – kinematic viscosity
κ – thermal diffusivity
D – horizontal extent



The Barrel of Ilmenau

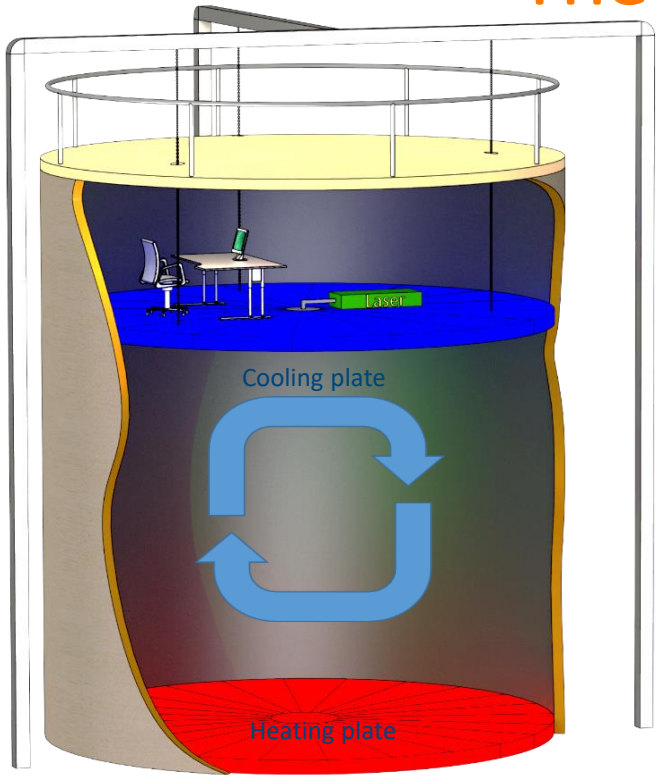


Figure: Test facility for Dust Devil-like vortices: Barrel of Ilmenau

Brief description of the test facility :

- Large Scale Rayleigh Bènard Experiment
- Air-filled cylindrical tank with a total diameter of 7m and a total height of 8m
- Bottom of the tank is a heating plate and the second plate above is the cooling plate
- Side wall completely adiabatic
- In order to ensure the existence of multiple convection rolls in the test section, the distance between the horizontal plates should be smaller then the diameter of 7m

Characteristics:

D =	7.15 m
H =	0.2 – 6.30 m
T_H=	10 – 80 °C
T_C=	10 – 80 °C
Ra=	$10^5 – 10^{12}$
Pr=	0.7
Γ =	1.13 – 35.75

Figure: Barrel of Ilmenau (Ilmenauer Fass)

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First Experiments

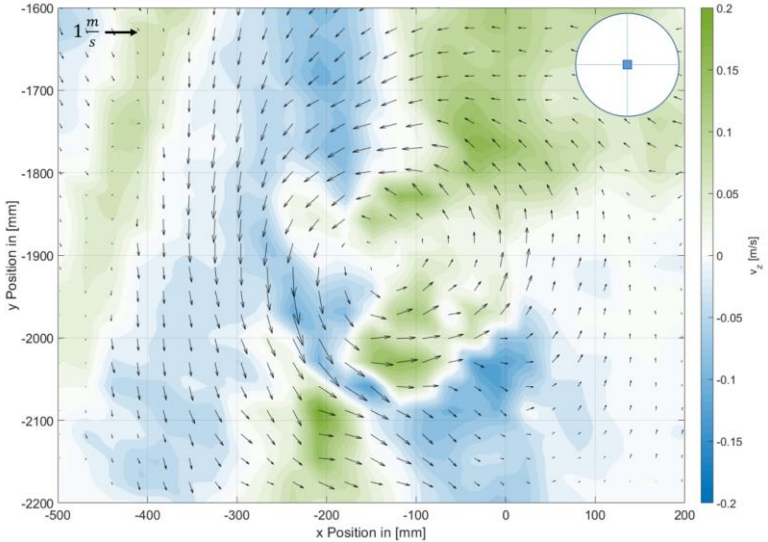
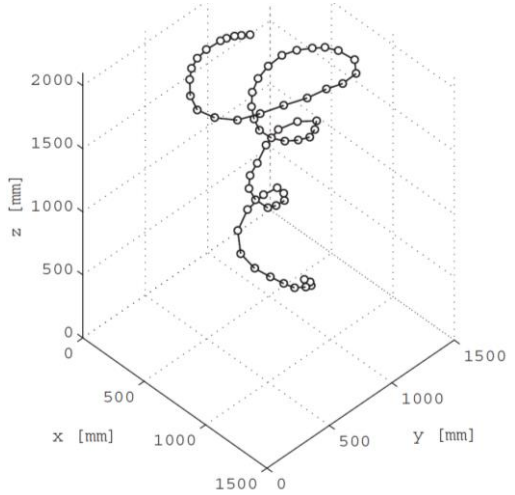


Fig.: StereoPIV (2018), Ra= $3.5 \cdot 10^{10}$, Pr=0.7, Γ=3



E. Lobutova (2010) : Investigation of large-scale circulations in room air flows using 3D-PTV (helium filled latex balloons)

- An important basis for this work is the fact, that such structures could already be measured in "Barrel of Ilmenau" in the past, but only in one plane (left) or with helium filled latex balloons (right)
- For a characterization of the 3D structure, a three dimensional optical measurement technology with small particles is necessary: **3D Particle tracking velocimetry (3D-PTV)**

Particle Tracking Velocimetry

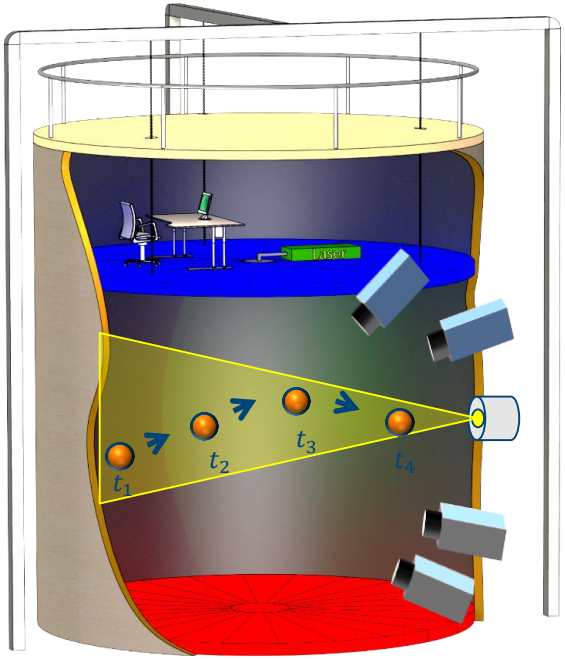
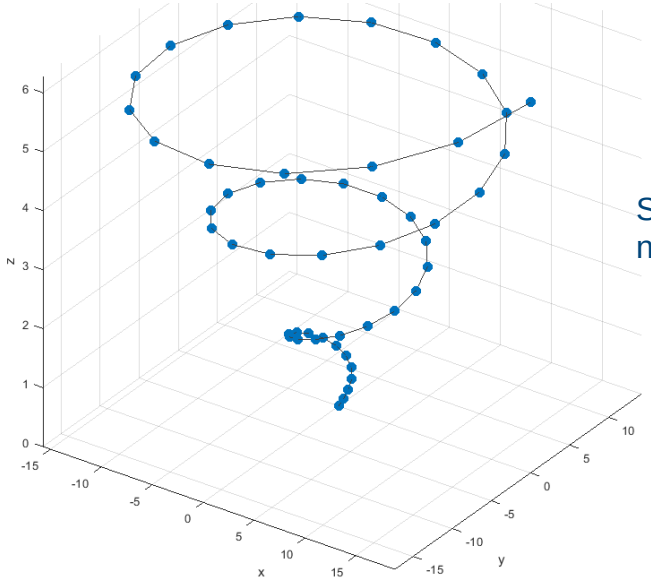


Figure: Test facility for investigation of dust devil-like vortices: The Barrel of Ilmenau

- 3D PTV is the reconstruction of a Lagrangian flow field
- Main idea: tracking of a particle in several time steps and calculation of the trajectory:



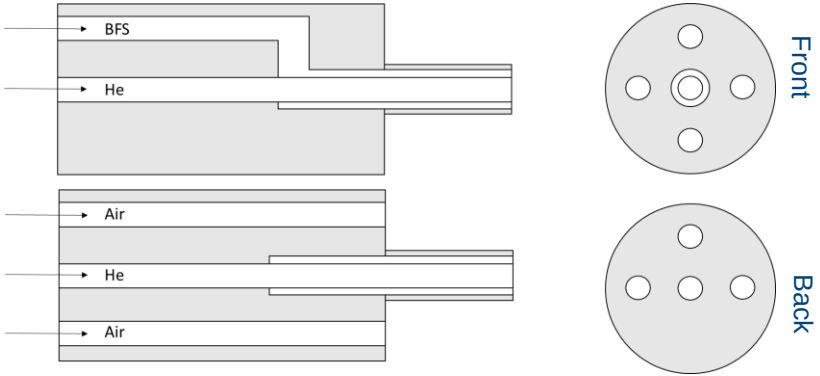
Several components are necessary (**see next slides**):

1. Buoyancy-neutral particles
2. Cameras
3. Illumination of Particles and Recordings

Measurement Technique: Particles

Particles for experiments: Helium filled soap bubbles (HFSB)

- **Main Challenge**: Generation of buoyancy-neutral particles with a appropriate diameter
- Commercial generators not produce such large particles, design of a new generator
- Basic structure of new generator: nozzle with a connection for helium (He), compressed air and soap solution (BFS)
- Helium and compressed air: regulation of volume flow with flow control valve
- Soap solution: regulation of volume flow with a dosing pump



Measurement Technique: Cameras

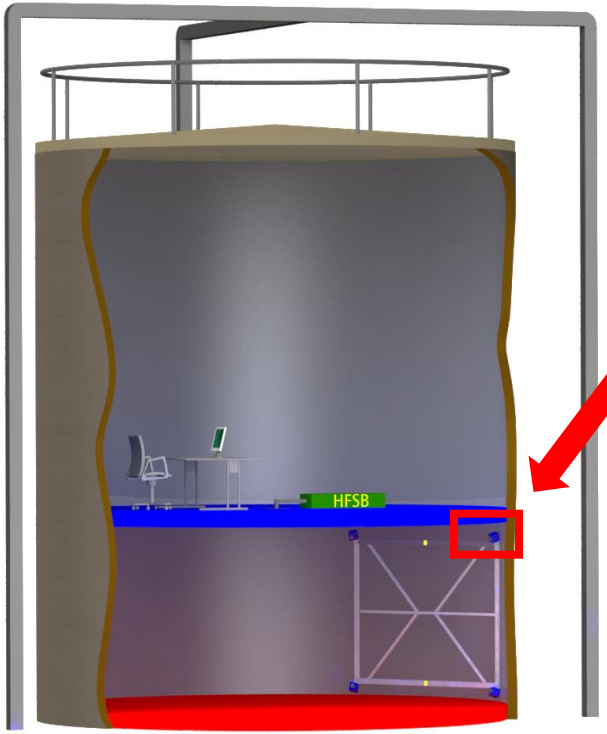


Fig: Barrel of Ilmenau

- Use of four Imager sCMOS cameras (Cam 1,2,3,4) inside of measurement volume
- Pictures of the particles at precise time intervals
- To calculate the position of a particle in a volume, a calibration is necessary
- For the calibration so-called targets are used (marks with known distances)
- Cameras should capture a large image section (right figure)

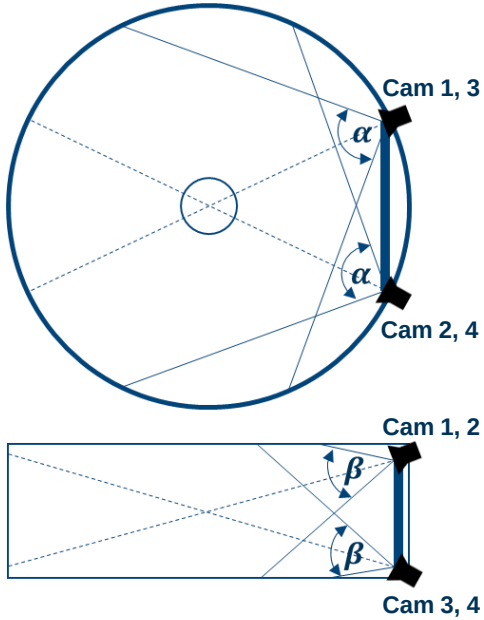


Fig: Top and side view of the measurement volume (Size of convection cell: d = 7.15m, h = 2.38m with opening angle of the cameras, Γ = 3, α = 90°, β = 75°. There are four cameras in total, whereby two cameras are located directly behind each other in the sketch

Measurement Technique: Illumination

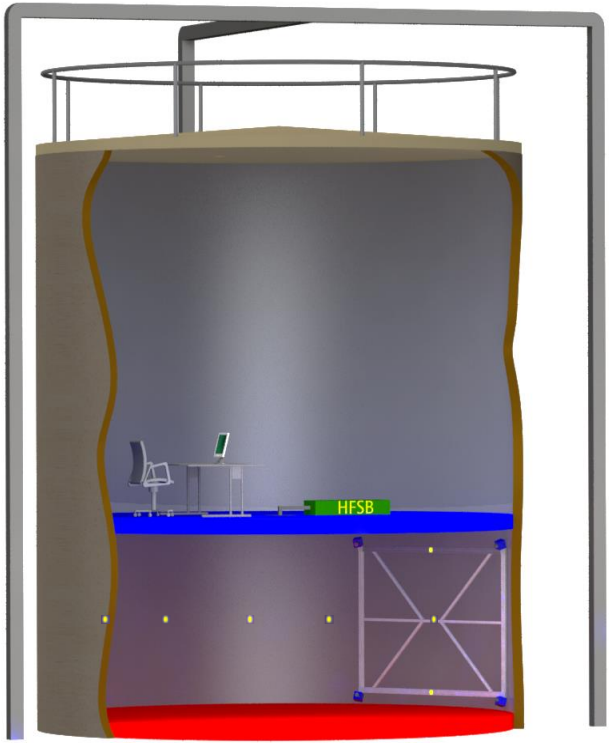
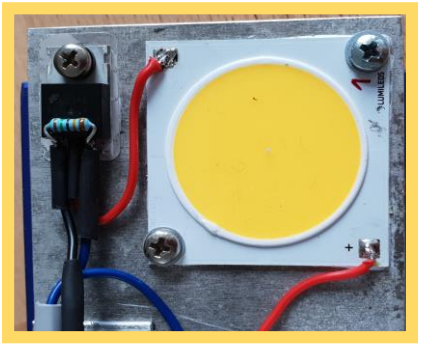


Fig: Barrel of Ilmenau: Yellow dots are the LEDs



High performance LEDs:

- Model: Luxeon CoB 1321
- Efficiency:> 150 lm / W
- Luminous flux: ~ 12,000 lm
- Total angle of light: 115 degrees
- Impulse mode (duration ~ 2ms)

- High light output for a volume of ~ 100 m^3
- Important for visibility of particles
- Small heat generation (water cooling)
- Uniform intensity over the entire measurement volume
- Synchronized with cameras

All challenges for a set-up to investigate dust devil-like vortices have been solved. This includes an optical arrangement of the cameras, the calibration, a homogeneous volume illumination and particles.

Measurements

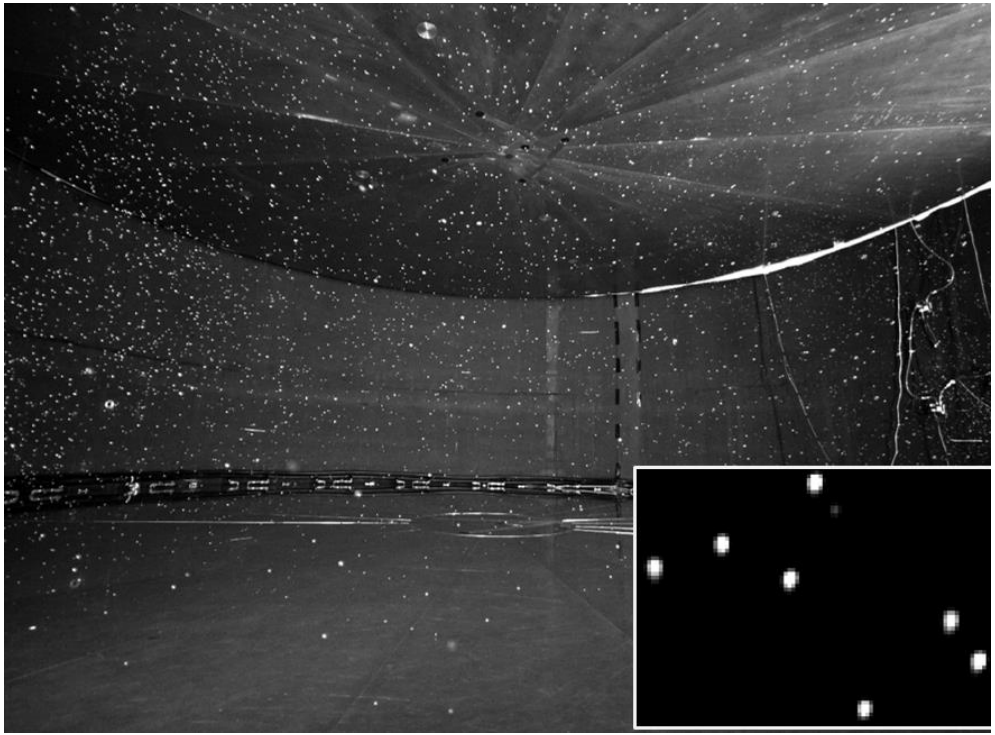


Fig: Complete raw image of one camera in the “Barrel of Ilmenau” with an aspect ratio of Γ = 3. Bottom: enlarge representation of the particles after image preprocessing

- Recordings: four cameras with image rate of 10 fps (frames per second)
- Rayleigh number is $Ra = 2.9 \cdot 10^{10}$ with a temperature difference of 20K and an aspect ratio of 3 (convection rolls, aspect ratio)
- After image acquisition and image preprocessing, we reconstruct the 3D position of all tracer particles for each time step and calculate the trajectories
- For calculation, we use the Shake-The-Box (STB) method (Schanz (2016): Shake-The-Box: Lagrangian particle tracking at high particle image densities)

Calculation of Trajectories

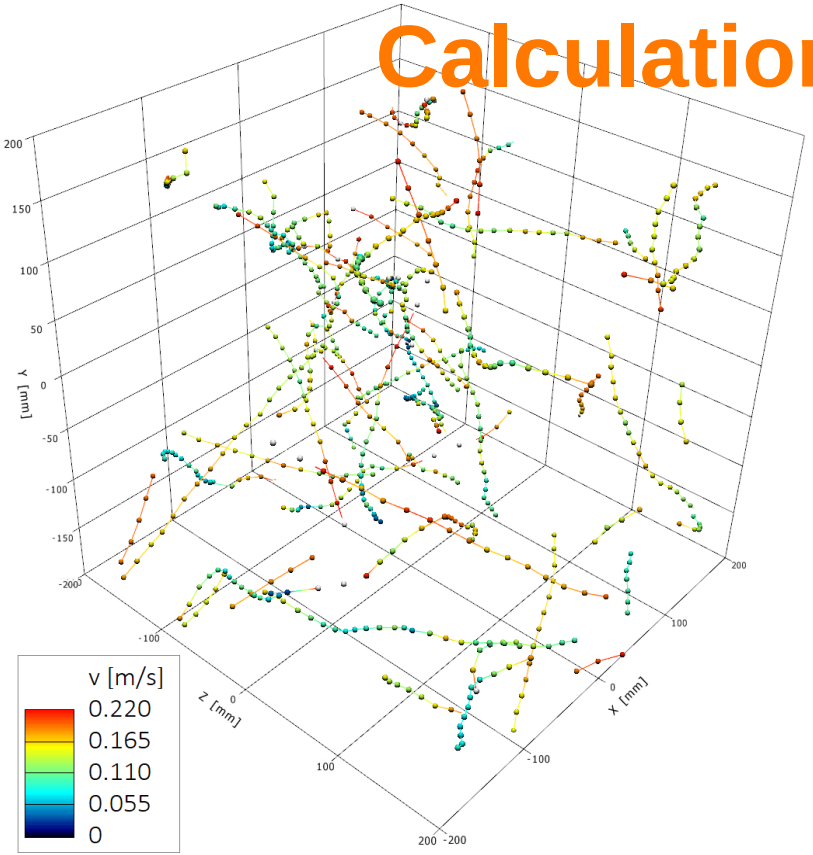


Fig.: Trajectories in the BoI with StB (reduced volume)

Summary

- Realization of a suitable experimental setup: 3D PTV
- Recording of particles
- Calculation of trajectories

Outlook

- Identification of dust devil like structures in the recordings
- Analysis of the dust devil structure
- Analysis: diameter, intensity, lifetime and the frequency of occurrence
- Dependence of vortex formation and number of convection rolls