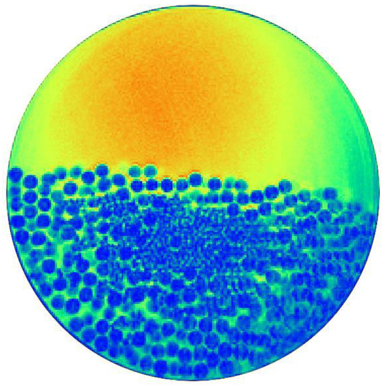
# Granular materials

**Tilo Finger, David Fischer, Frank Rietz, Sandra Wegner, Kirsten Harth, Ralf Stannarius**

- Axial segregation in rotating cylindrical mixers
- Segregation in rotating spherical mixers
- Diffusion in granular mixtures
- Convection and segregation in rotating flat containers
- Shear zone refraction in layered granulate
- Orientational order and shear alignment of anisometric grains
- Granular gases of elongated grains



# Axial segregation of granular material in a long horizontal rotating drum

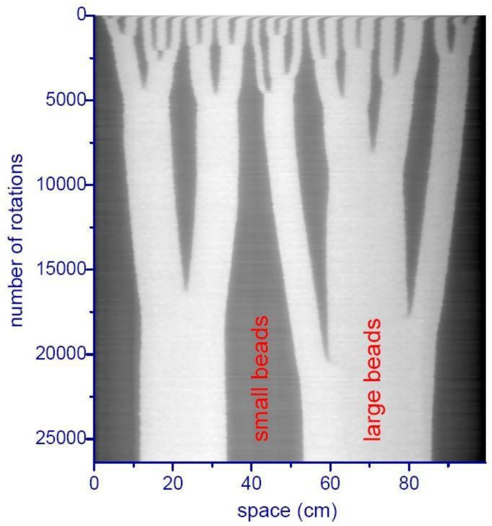
- Granular mixtures of particles which differ in size, density or surface roughness show the tendency to segregate under a wide variety of flow conditions
- A typical example is the segregation along the axis of a partially filled horizontally rotating drum
- The system shows a very interesting dynamics:
  - After a few rotations the small grains forms a core along the axis of the drum (radial segregation).
  - A few rotations later, this core becomes unstable and a stripe pattern appears (axial segregation).
  - After the formation of the stripe pattern a so-called coarsening sets in. This means that individual stripes shrink until they vanish, while other stripes grow in size.
- Until now, the coarsening dynamic is only poorly understood .

| | |
|---|---|
|  | initial mixed state |
|  | after 500 rotations |
|  | after 23000 rotations |

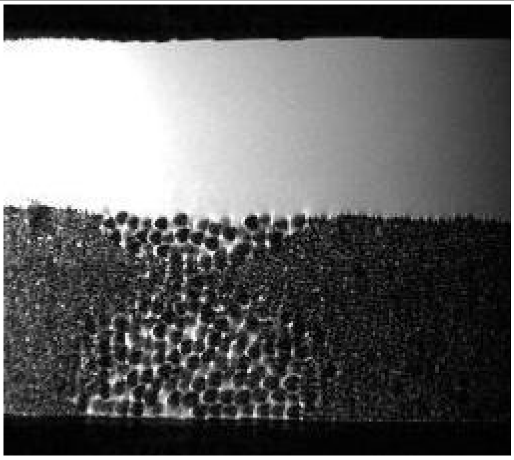
- Advantages of the system compared to other segregation experiments:
  - The energy can be supplied continuously and uniformly over arbitrarily long time periods.
  - The stripe pattern can be observed straightforwardly.
  - The time evolution of the visible stripe pattern can be mapped in space-time plots.
- Elucidation of the 3-dimensional particle distribution is one important prerequisite to understand the mechanism of coarsening.
- The 3D particle distribution is investigated non-invasively by Magnetic Resonance Imaging (MRI). Experiments were performed in collaboration with the LIN Magdeburg [Finger2006,Finger2007,Fischer2009,Naji2009].

Our particular topic of interest is the coarsening of the stripe patterns, the distribution and the axial transport of grains:

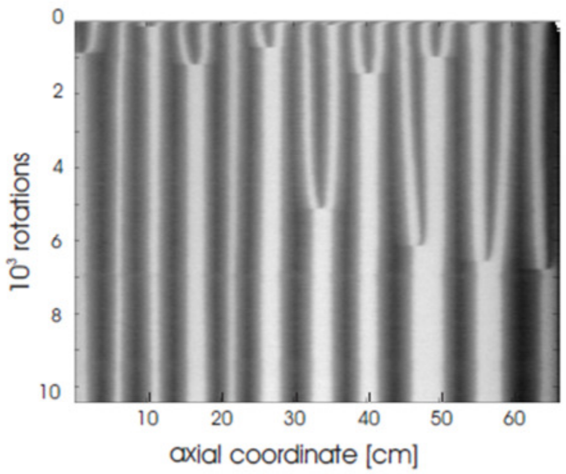
- What are the scaling laws of the coarsening process?
- What is the drivingl mechanism of coarsening?
- How can the axial grain transport be described?
- What is the internal structure of the segregation pattern?

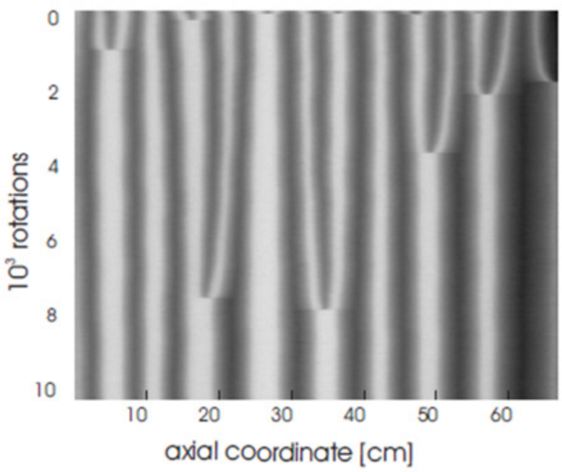



Space time plot of a striped segregation pattern (left), the cylindrical drum of 38 mm diameter and 1m length is half filled with a 50:50 mixture of 1.5 and 0.55 mm diameter glass beads. The characteristic feature is the logarithmic decay of the number of segregation stripes. In the investigated mixtures, stripes of small beads lose material to neighboring stripes or gain material from there.



Example: experimental cross section (sagittal section, along the vertical midplane of the tube). The tube is filled with glass beads in water. Bright areas reflect the proton signal from the surrounding water. One acknowledges two stripes of the small bead species separated by a band of large beads. In the core, one observes a channel of small beads connecting the two outer stripes. This channel is essential for the stripe dynamics.

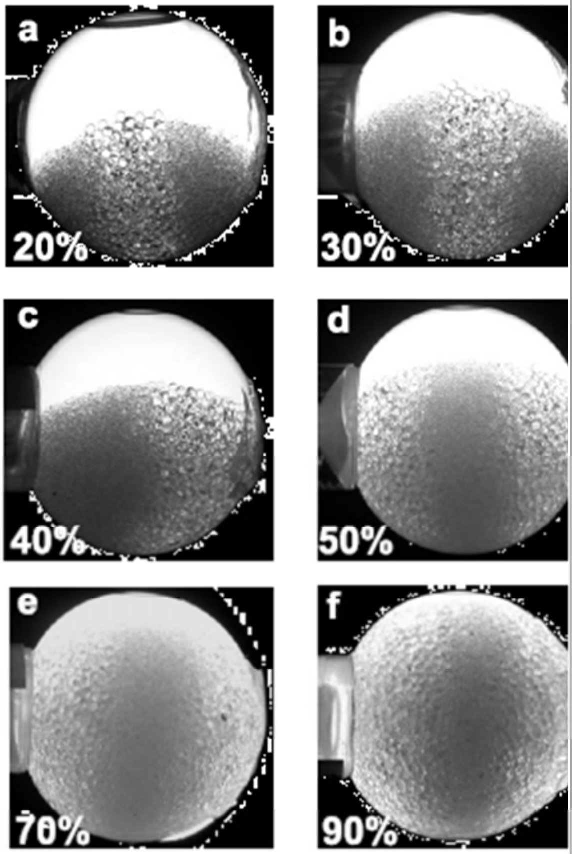



Influence of the interstitial fluid: Space-time plots of the coarsening of segregation patterns, mixture of glass beads with 1.5 mm and 0.55 mm diameter. The granulate is embedded in a 80% glycerol in water mixture (left) and a 40% glycerol in water mixture (right). The viscosity of the embedding fluid has little influence on the dynamics of the stripe pattern [Finger2007]

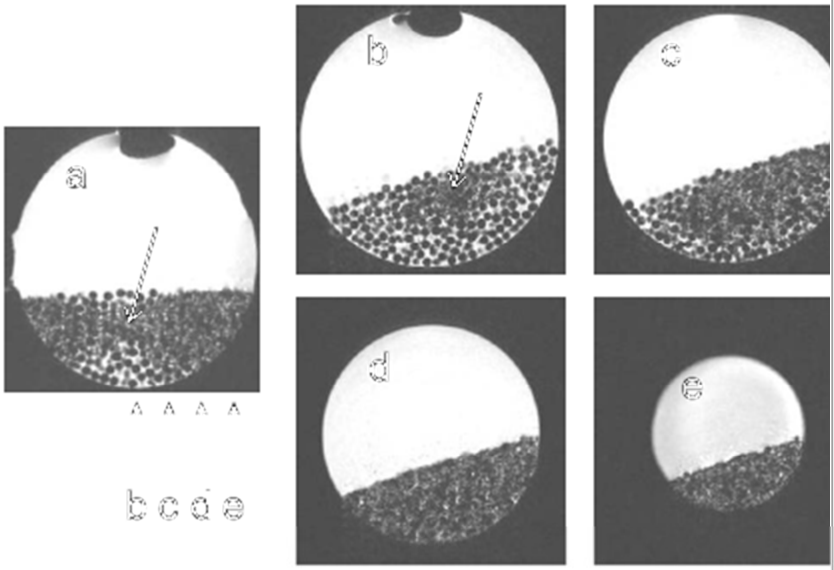
# Segregation in rotating spherical mixers

A spherical container (37 mm diameter) filled with a bidisperse mixture of spherical beads (0.5 mm and 1.5 mm diameter) is rotated about a horizontal axis at rotation rates of several rpm. The initial fill level determines the type of segregation pattern that is formed. At low fill levels, small beads occupy the poles while large beads occupy the equatorial zone. At high fill levels, the positions of stripes of small and large beads appear interchanged, small beads occupy the equatorial zone, large beads the polar zones. The mechanism is not fully understood yet [Naji2009].

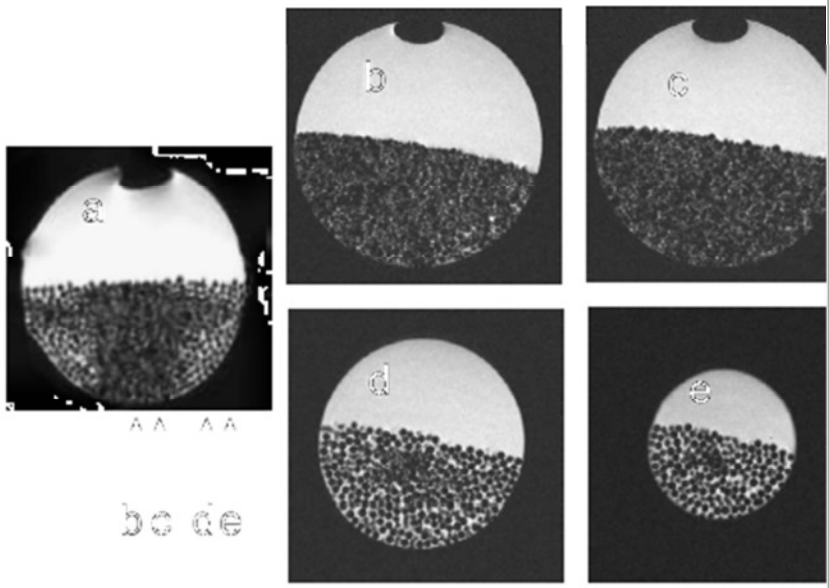



Two regimes are observed in a spherical mixer that rotates about a horizontal axis:

- when the fill level is below 30%, the small beads occupy the lateral zones and large beads are located in the central zone
- when the fill level is above 50%, the large beads accumulate in the lateral zones and small beads form the central zone
- at fill levels around 40%, a transition region is found. Often, only two zones are formed there




Vertical MRI slices of the SLS (small-large-small) segregation pattern at low fill levels. Slice a contains the rotation axis, slices b-e are normal to the rotation axis. Water appears bright in the images, the beads black. At the top, an entrapped air bubble is seen. A core of small beads links the two polar segregation bands.

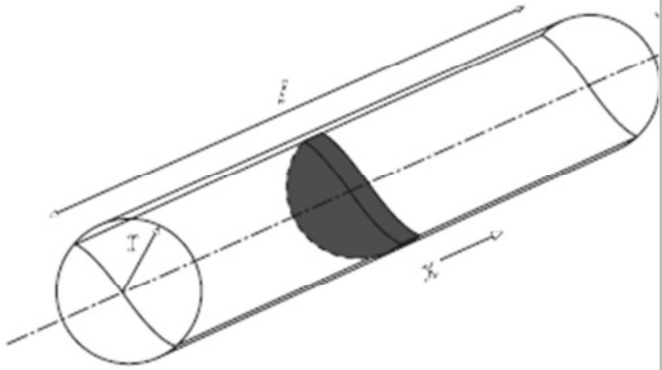


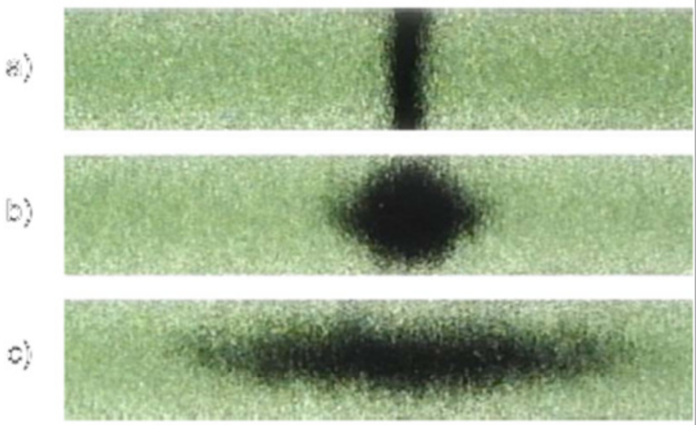

Vertical MRI slices of the LSL (large-small-large) segregation pattern at high fill levels. Slice a contains the rotation axis, slices b-e are normal to the rotation axis. Conical tongues of small beads extend into the polar bands of large beads.

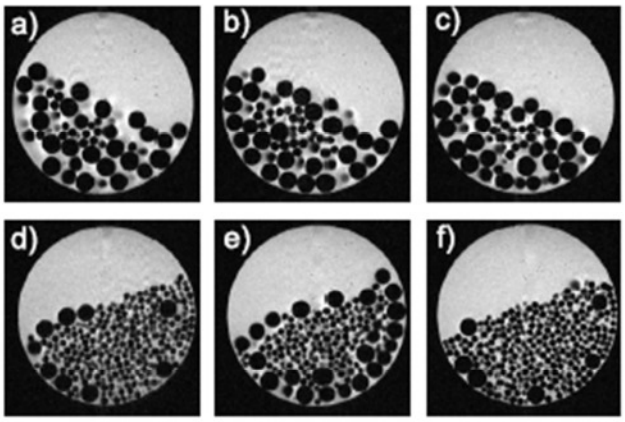
# Diffusion of granular material in a long horizontal rotating drum

Measurement of the particle dynamics in a rotating mixer [Fischer2009]

- preparation of a 'pulse' of grains in a rotating mixer with 50% fill height (right), a slice of large/small glass beads is prepared initially in a bed of small/large beads
- Diffusion of glass beads observed optically, view onto the flowing layer of the rotating cylindrical tube (bottom left). Small beads (black) diffuse axially into regions of large beads (light green), images were taken after a) 0 rotations, b) 30 rotations and c) 300 rotations.
- MRI slices of the cylinder (bottom right), the bright regions contain water, the glass beads appear as black shadows. From the particle positions, the time dependent axial distribution and the character of the diffusion are obtained.

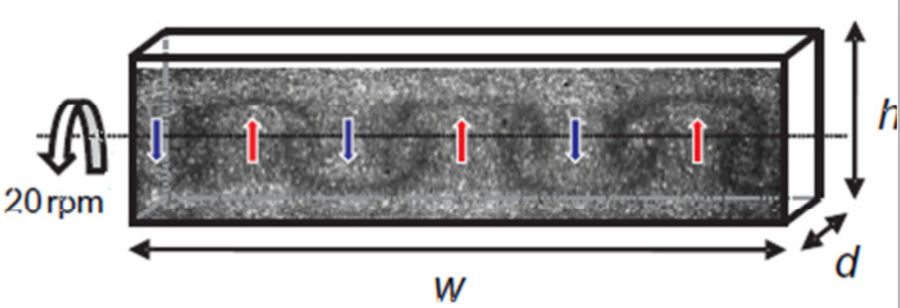


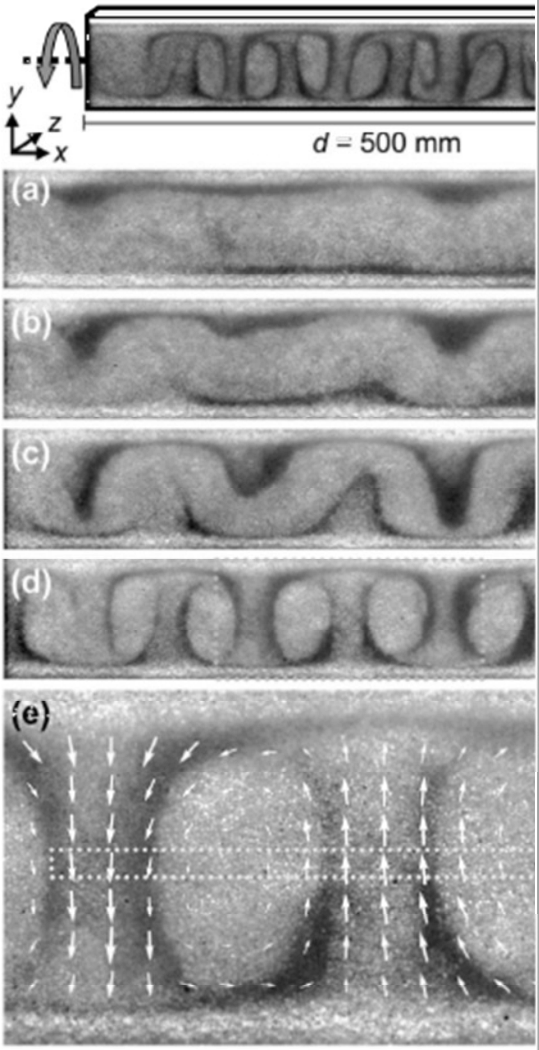


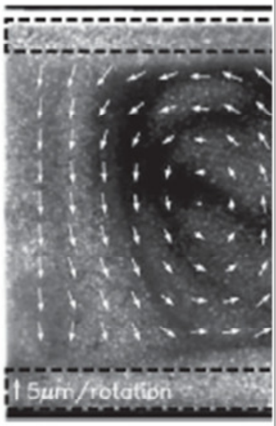
# Convection and segregation in rotating flat containers

A flat container (approximately 5 - 10 particle diameters thick, see image) is filled with a bidisperse mixture of grains and rotated about a horizontal axis. We observe two different scenarios, depending upon the fill level. At low fill level, chute flow leads to a lateral segregation into stationary or traveling stripes, coarsening of the stripe pattern can occur. In cells with high fill level we observe convective patterns.

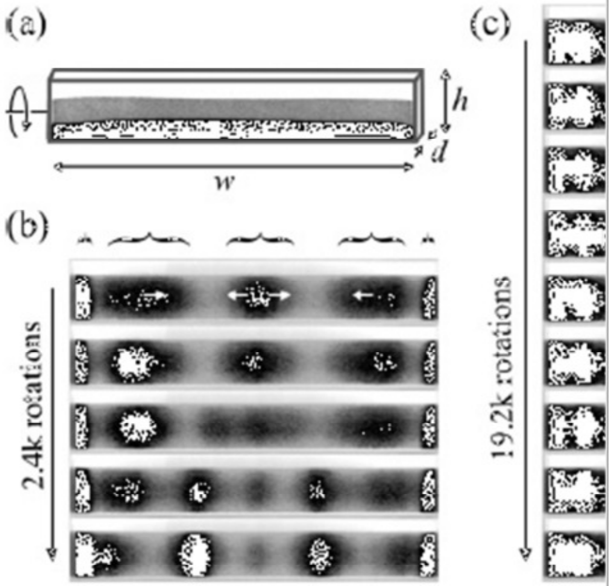



Convection rolls in a cell with high fill level [Rietz2008,Rietz2012NJP]



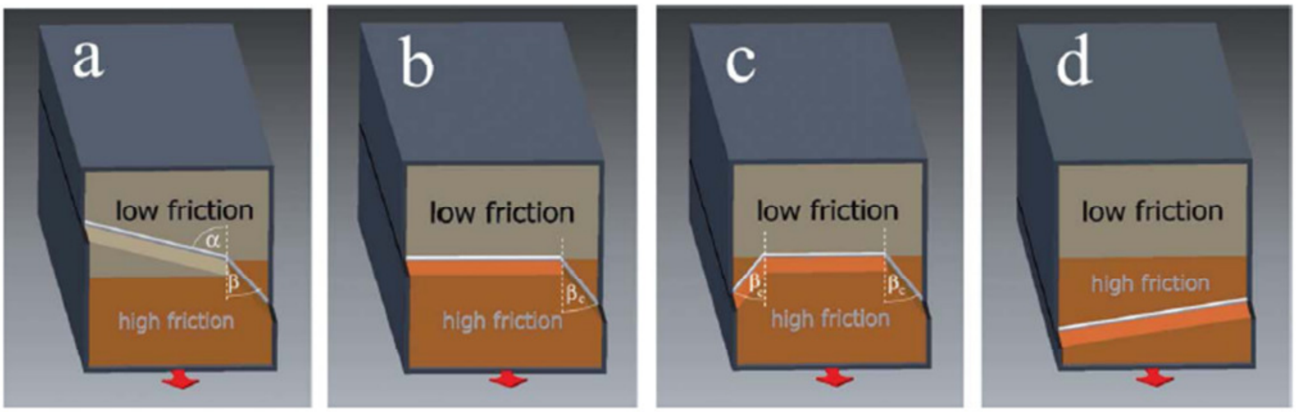

In containers with aspect ratio close to one, single rolls form. In contrast to multiple rolls in cells with larger aspect ratios, these single rolls exhibit fluctuations, cessations and spontaneous reversal of the convective flow [Rietz2012PRL].



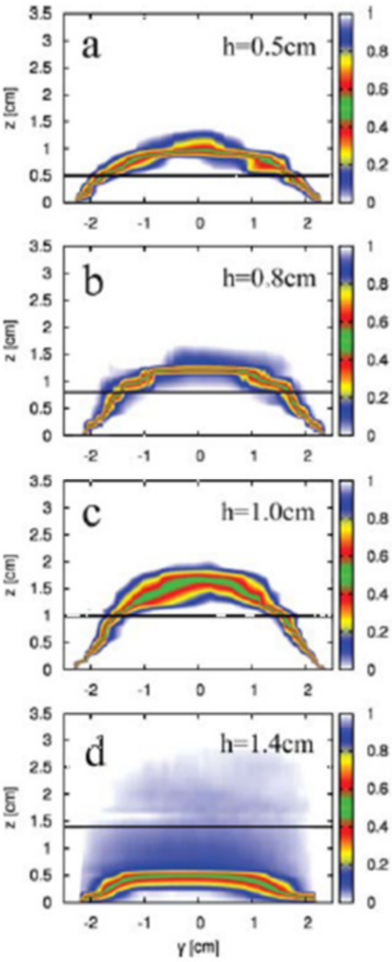

In cells with low fill ratio, the granulate segregates into lateral stripes. These stripes can spontaneously form or decay, merge, and move in axial direction. Traveling wave patterns have been observed [Rietz2012PRE]. These patterns can show quasi-periodicity over long periods. During long-term experiments in an individual cell, the spontaneous transition between different periodic traveling wave patterns can take place spontaneously.

# Shear zone refraction in layered granulate

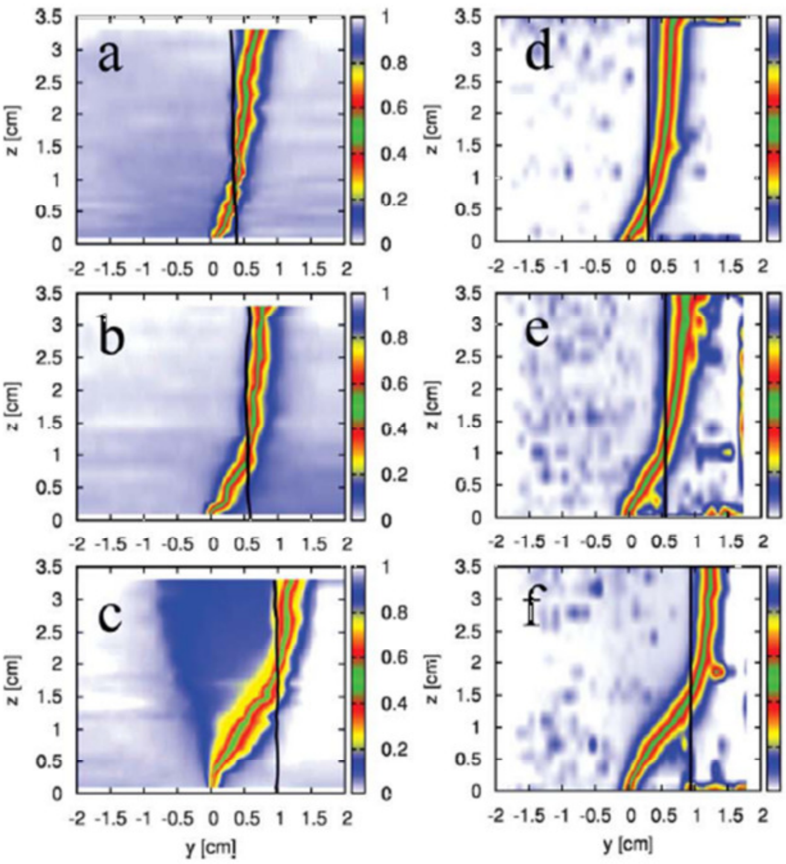
in collaboration with T. Börzsönyi (Hungarian Academy of Sciences, Budapest)




**Gedankenexperiment** [Börzsönyi2011]**,** two layers of grains, the upper one with low friction, the lower one with high friction:
When the bottom (u-shaped) slider is moved respective to the upper counterpart, a shear zone separates material moving with the bottom slider from material remaining at rest with the top slider. This shear zone selects a shape where it minimizes friction,. Similar to Fermat's principle in optics. In first approximation, the integral of the friction coefficient along the shear zone is minimized. The result is a shear zone geometry analogous to Snellius's law of refraction and reflection in optics.



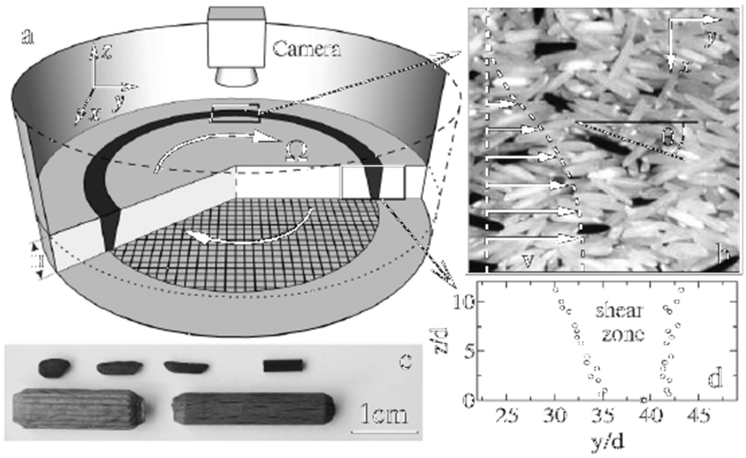

experimentally determined shear zone geometries in vertically stacked layers of korundum (high friction, bottom) and glass beads (low friction, top). The zone geometries were determined by excavation of color-labeled layers



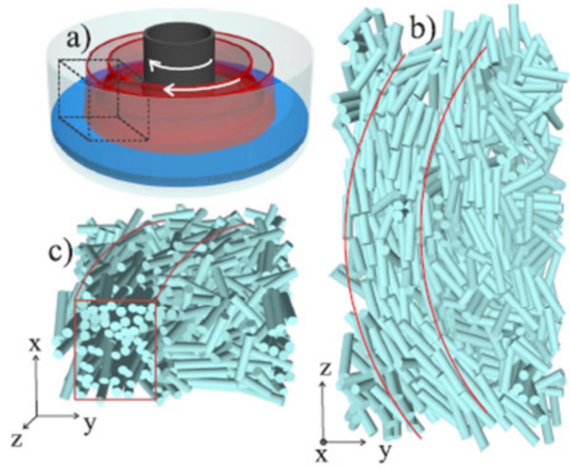

experimentally determined shear zone geometries in horizontally stacked layers of korundum (high friction, left) and glass beads (low friction, right). The zone geometries were determined by excavation of color-labeled layers (a-c) and MRI imaging of poppy seed tracers (d-f)

# Orientational order and shear alignment of anisometric grains

Anisometric grains can be aligned by shear flow. We study the orientational order and shear alignment of anisometric grains by means of optical techniques and three-dimensional tomographic imaging (X-ray Computed Tomography and Magnetic Resonance Imaging)




Shear experiments in a container with split-bottom geometry: A disk on the container bottom with a smaller radius than that of the cylindrical container is rotated. The granulate in the container (rice in the picture above) is sheared and it forms a localized shear zone. Rodlike or elongated cylindrical grains align in a preferential orientation, a few degrees off the shear flow direction. [Börzsönyi2012PRL,Börzsönyi2012PRE]

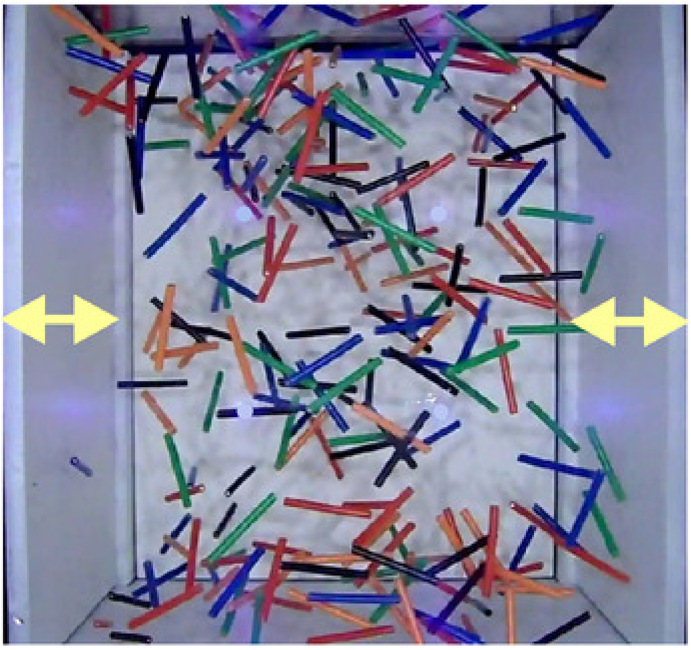



X-ray CT of an ensemble of sheared wooden cylinders (25 mm length, 5 mm diameter). Image a) shows the shear geometry of the cylindrical split-bottom cell, the shear zone (red) and the section of the CT image (dashed black box); images b) and c) show reconstructions of the particles from the CT data [Wegner2012].

# Granular gases of anisometric grains

A granular gas of rodlike grains is studied under weak excitation, to identify its statistical properties. An interesting question in such an ensemble is the test of the equipartition of mechanical energy on the different translational and rotational degrees of freedom.
The rods of about 12 mm length and 1.3 mm diameter are contained in a cuboid box with dimensions of 8 x 10 x 6 cm. Three walls of the box vibrate with 30 Hz frequency and a vibration amplitude of the order of 2 mm (image).
The experiment was performed in a suborbital rocket that provided approximately 70 seconds of microgravity.

The first experiment was designed and performed within the REXUS-10 campaign of DLR, SNSB and ESA, project GAGa (Granular Anisotropic Gases). The team members GAGa were K. Harth, T. Trittel, U. Kornek, U. Strachauer, K. Will, and S. Höme. Data evaluation and modeling are in progress.



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