ESRF	**Experiment title:** Dynamics of fluidized wet granulates	**Experiment number**: MA 601
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Names and affiliations of applicants (* indicates experimentalists):

*Stephan Herminghaus, *Zeina Khan, *Mario Scheel,
MPI for Dynamics and Self-Organization, Bunsenstr. 10, D-37073 Göttingen.

*Ralf Seemann,
Experimental Physics, Saarland University, D-66041 Saarbrücken and
MPI for Dynamics and Self-Organization, Bunsenstr. 10, D-37073 Göttingen.

Report:

A collection of macroscopic grains has different physical properties from a bulk solid or fluid. For example, in a narrow pipe a granular material can flow as a liquid, but it can also jam the pipe like a solid. The statics and dynamics of granular materials are practically relevant to numerous industries and their unusual physical properties have become the topic of an active field of research [1]. Although most of this research focuses on dry grains, every child knows that the properties of a sandpile change dramatically when the sand is wet, and that the resulting stiffening can be exploited to construct sandcastles. When a small amount of fluid is added to dry grains, the fluid will form bridges at the grains' contact points. The surface energy of the liquid bridges results in an attractive force between grains in contact which is absent in dry granulates, therefore, wetting changes the medium from one with only repulsive interactions between the grains to one with both repulsive and attractive interactions [1-4]. Given that the microscopic physical interactions between the grains are fundamentally different for wet grains, it is not plausible to apply the extensive knowledge base developed for dry systems to wet ones. For example, studies of diffusion in dry granulates yield a variety of results concerning the presence of subdiffusion and transitions from subdiffusive to diffusive flow regimes. The occurrence of these results depends intimately on numerous parameters, like the depth of the flowing layer in the granulate [5, 6] and grain packing density [7], and it is our goal to determine what effect the presence of a wetting fluid will have on the diffusivity.

In our experiments we placed granular samples consisting of glass or steel beads on an electromagnetic shaker and agitated the samples continuously while obtaining ultrafast x-ray absorption images. Tracer particles (such as BaTi, lacquer coated gold, or lead grains), chosen to possess a larger x-ray absorption than the surounding media, were embedded in the sample in order to determine the trajectories of particles within the flow while being fluidized. Silicone oil was used as the wetting liquid in these experiments since its boiling point is above 250 ^{o}C and no radiation damage had been detected in previous experiments. We have varied numerous physical parmeters in the data collected in order to determine the influence of the driving frequency and acceleration, the wetting content, the viscosity and surface tension of the wetting fluid, the inelasticity of the granular material, and the container dimensions on the dynamics of this system.

From absorption images taken at high speeds we were able to reconstruct the tracer particles' 2D trajectories using image processing techniques and a predictive particle-tracking algorithm [10]. Since the images were captured at the same frequency as the driving, the container appears fixed in our analysis. In figure 1a an absorption image of a dry sample driven with a frequency of 250 Hz and an acceleration of 7 g is shown with the reconstructed trajectories of selected tracer particles superimposed onto the image. Typically we captured images for hundreds of seconds up to several ten minutes and have on the order of 50,000 data points per tracer trajectory in order to obtain good statistics, but in the figure below the time axes of the trajectories are truncated for clarity. In dry samples convective flow is usually observed, along with caging motion as shown in figure 1b. In contrast, figure 1c shows an absorption image taken of a wet sample agitated at a frequency of 250 Hz and an acceleration of 8 g. Typical features present in the tracers' trajectories consist of caging as illustrated in figure 1d, as well as slower convective transport when compared with dry samples.

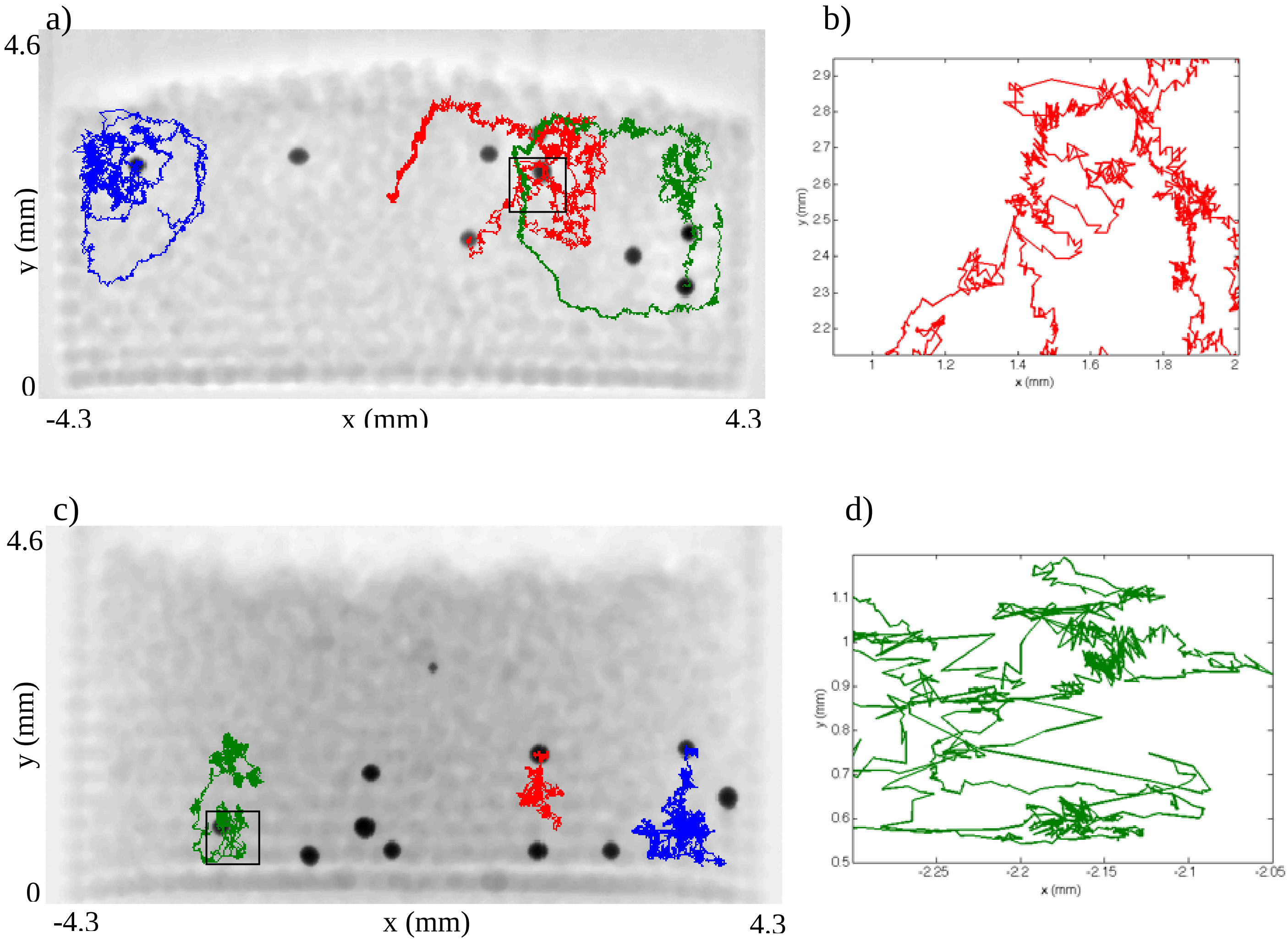

Figure 1. Typical x-ray projection images of vertically agitated glass spheres with lacquer coated gold tracer particles embedded in the sample to track the flow patterns. **a)** The dry sample was shaken at a frequency of 250 Hz at an acceleration of 7 g (1 g corresponds to 9.8 m/s^2). The superimposed curves correespond to trajectories of selected tracer particles being tracked for 40 s, and these curves were reconstructed from 10,000 absorption images. **b)** Detail of a single tracer's trajectory from (a). **c)** This sample, wetted at 2% by volume, was shaken at a frequency of 250 Hz at an acceleration of 8 g. The trajectories displayed here correspond to a tracking time of 120 s, and these curves were reconstructed from 30,000 absorption images. **d)** Detail of a single tracer's trajectory from (c).

We have examined the velocity statistics of the data analysed to date, and have found that the velocity distributions clearly deviate from a Gaussian distribution; this is particularly apparent at high velocities where there is a significant overpopulation of the distribution tails, as shown in figure 2a. A detailed analysis of the high velocity tails has shown that a majority of the data sets are best described by an exponential function, in agreement with observations made in quasi-2D dry granulates shaken at low accelerations [11,12]. However

these are the first such obervations made in a fully 3D granulate with bulk imaging under a wide range of experimental conditions, and could only be achieved through the use of intense synchrotron radiation and fast imaging techniques. In runs where a mean flow profile can be determined, we find that velocity fluctuations also deviate from a Gaussian distribution, as shown in figure 2b, which is characteristic of anomalous diffusion. While the corresponding vertical velocity distributions are not shown here, they display the same features as the horizontal distributions, in addition to a slight assymmetry at negative velocities due to the presence of gravity. Our ongoing analysis of the data includes a detailed investigation of the the anomalous diffusion present in this system, as well as the properties of the crossover to diffusive behaviour.

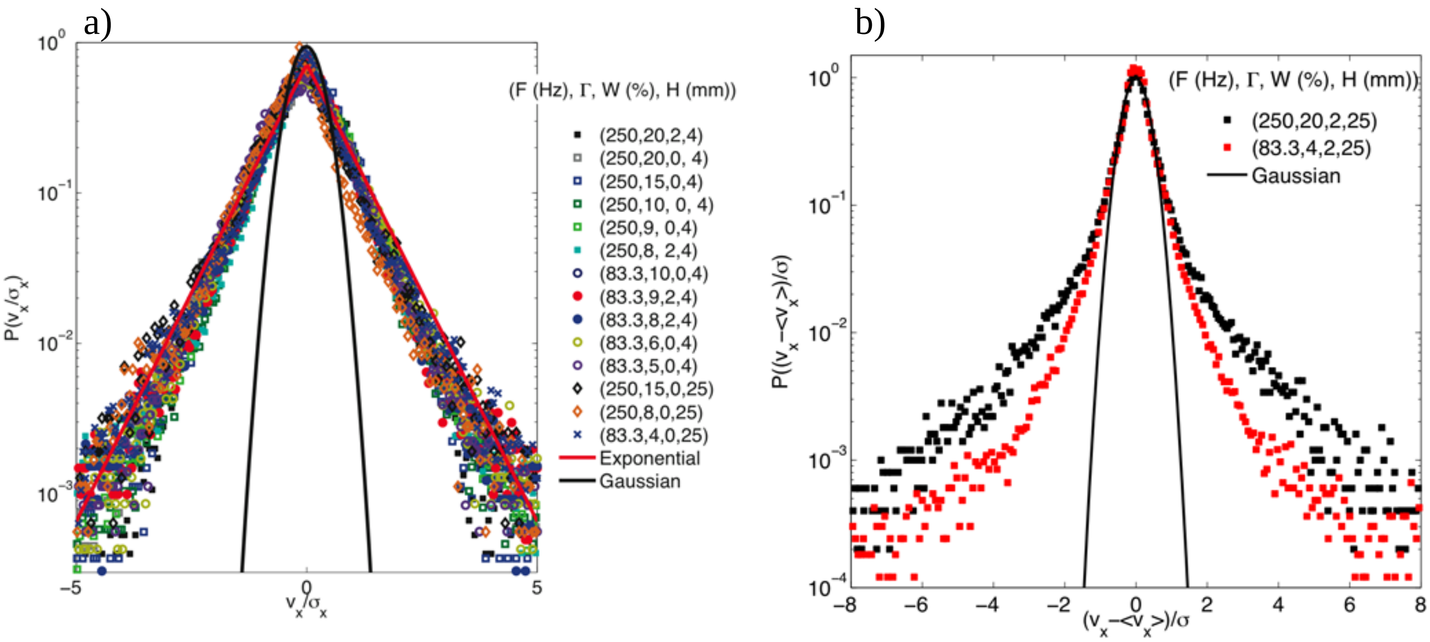

Figure 2. a) Horizontal velocity probablity distribution function, where the velocities are rescaled by their respective characteristic velocites $\sigma = <v^2>^{1/2}$. Gaussian and Exponential distributions are additionally shown as a guide to the eye. The data was obtained from numerous runs obtained for different driving frequencies F, accelerations Γ, wetting contents W, and filling heights H. **b)** Distribution functions of horizontal velocity fluctuations from selected runs.

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