# The start of granular flow

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- Experimental study of how do grains start to flow
  - Image particle arrangement in jammed state (preliminary).
  - Follow failure of jammed state and start of flow.
- **Questions:**
- Generic features of flow start?
- Role of contact network?
- Relation to steady state flow?

Why should I care about the onset of granular flow?

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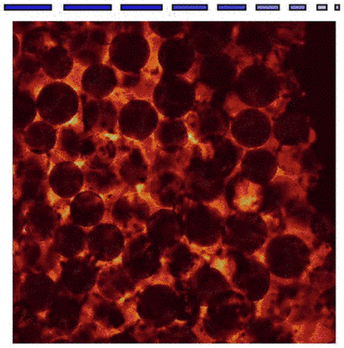
# Direct observation of microscopic structure

**Looking inside 3D granular matter**

- Granular material immersed in index matching fluid stained with laser dye:

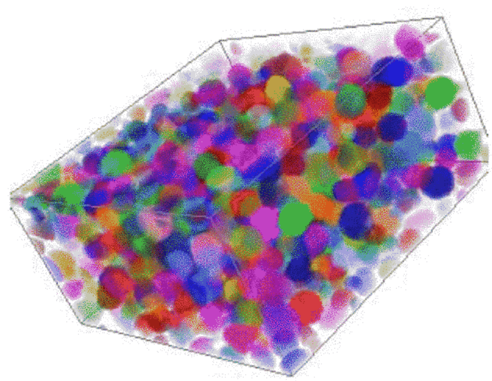
Confocal Microscopy



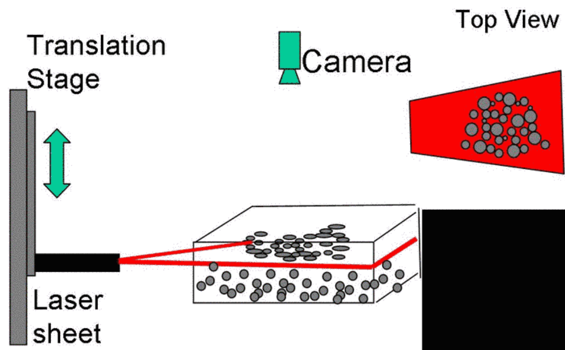
- Dry granular material:

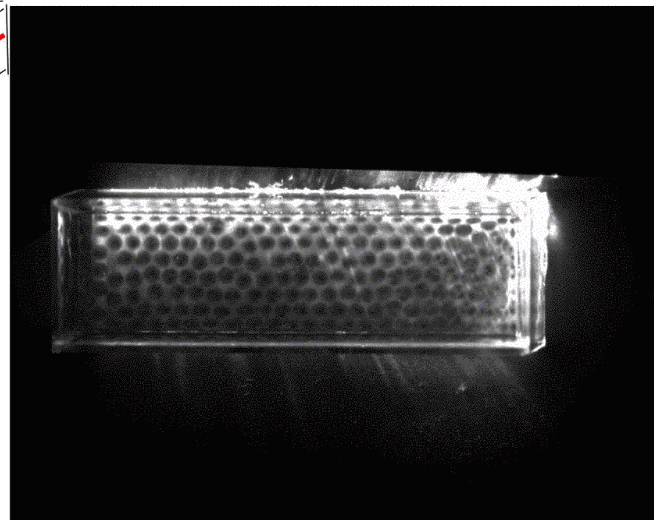
Synchrotron x-ray microtomography

(with R. Delanney and P. Richard, Univ. Rennes).

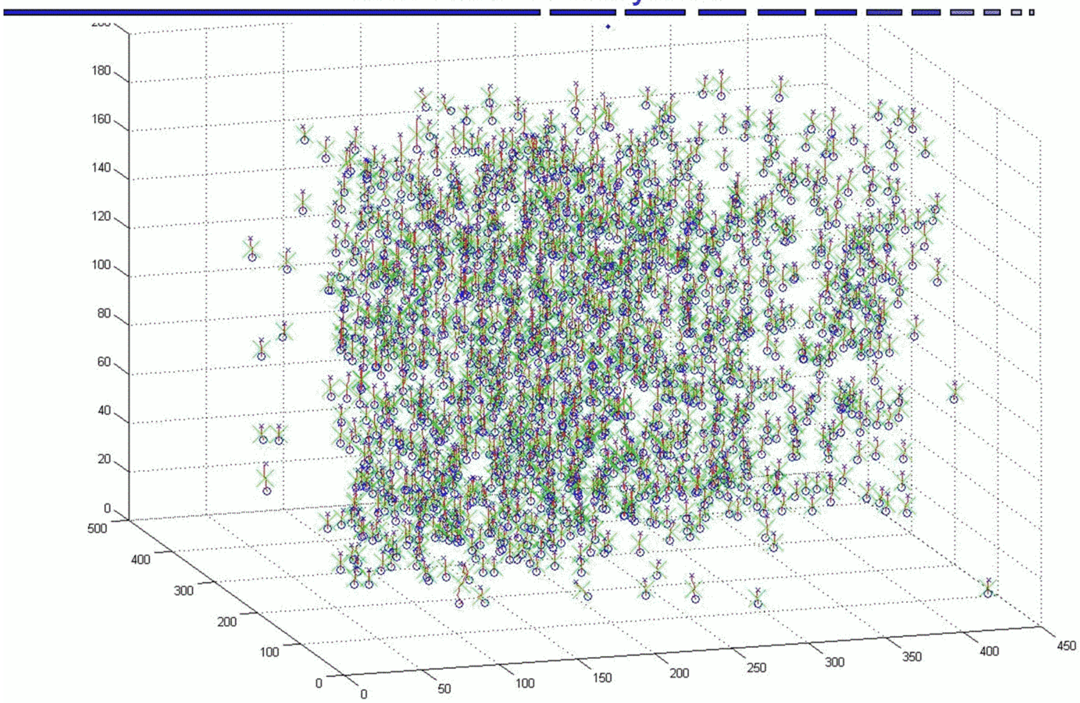


## Laser sheet scanning for 3D imaging



## First 3D reconstructions: Jacco Hettinga, Univ Twente and Univ. of Maryland




Expanded from 2D Matlab particle finding code from Stefan Koehler group

## Measures of the particle arrangement

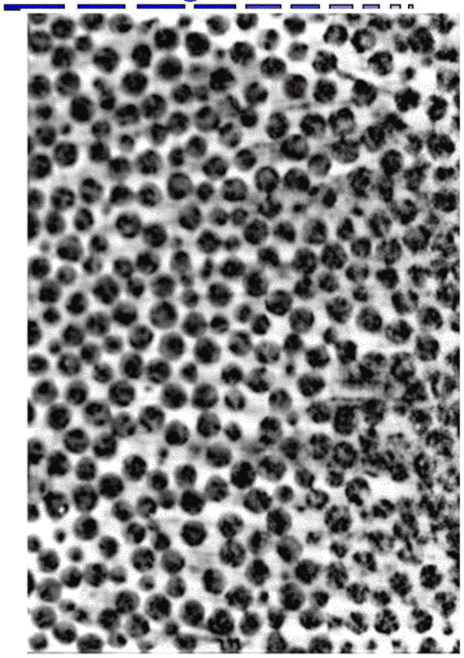
True Contact network and force transmission difficult to determine in 3D.

Instead:

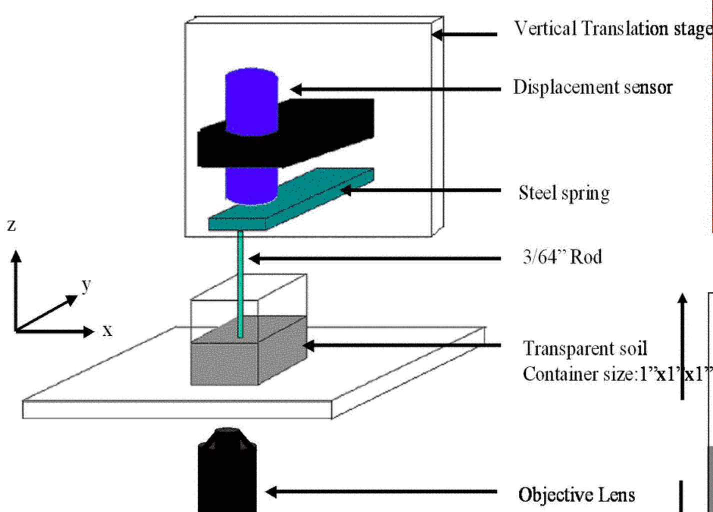
- Voronoi Cell Measures
- Correlations

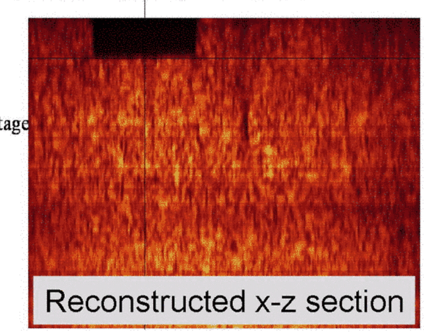
***Or: Destructive, indirect measure of contact network and force transmission:***

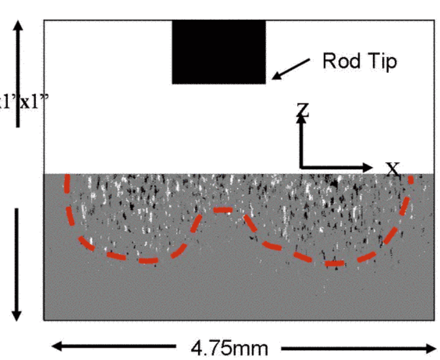
Measure particle motion during failure of jammed state



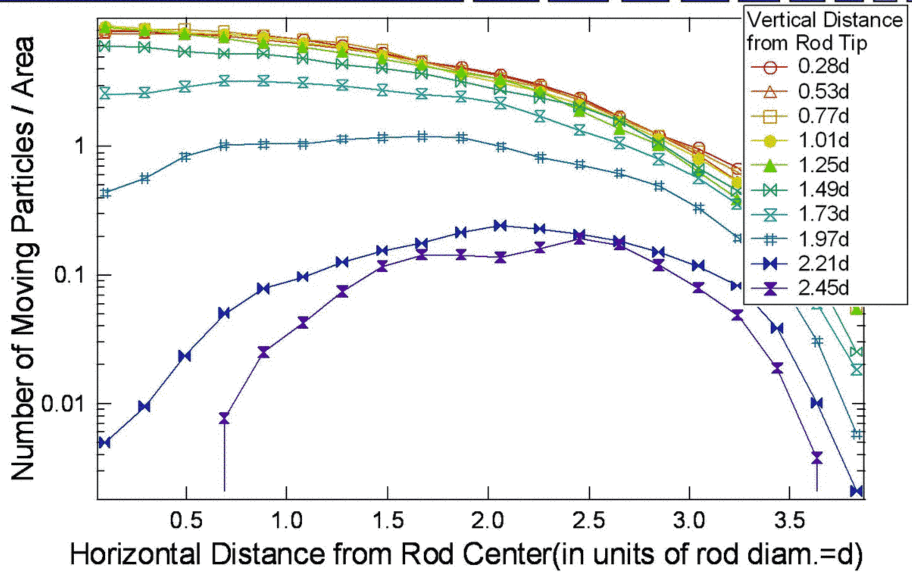
## Are contact network and failure related?



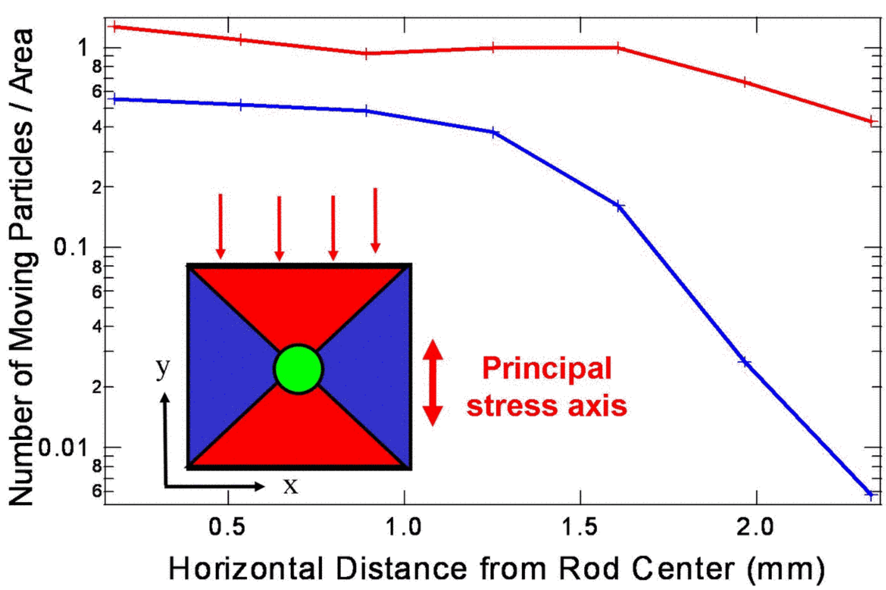



## Shear Zone Shapes at Various Depths

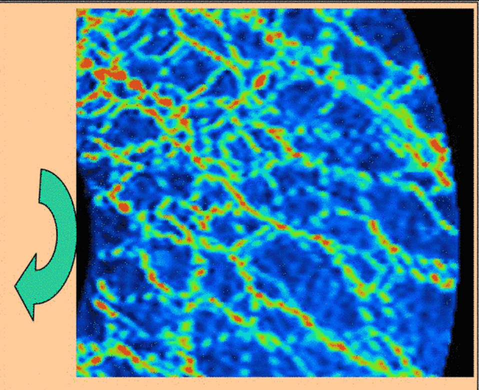



- Particle motion restricted under the rod at greater depths.



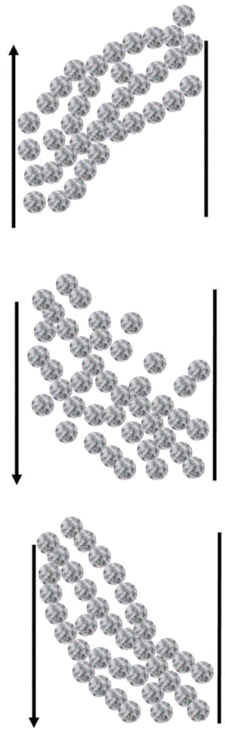

Principal stress axis and particle motion during failure are related.

## Controlled failure of contact network



2D experiments (Utter and Behringer, PRE)

1. Initial Condition: Sudden stop from steady state shear
2. Reverse shear
   - Network breaks
   - Network reforms
3. Steady state



Toiya, Stambaugh, and Losert, PRL 2004

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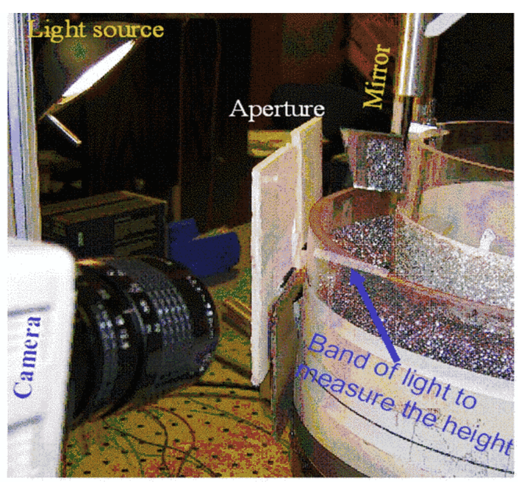
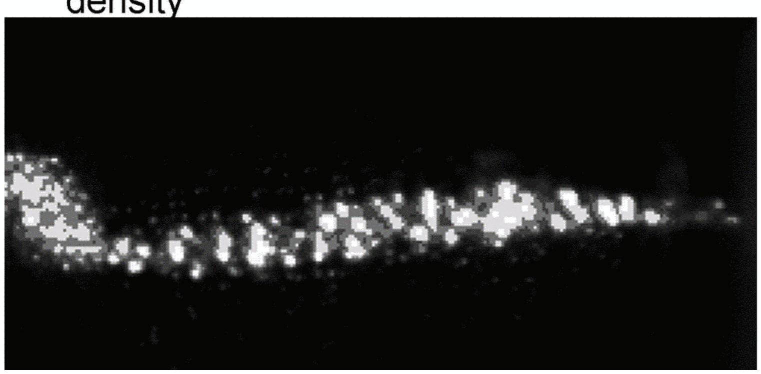
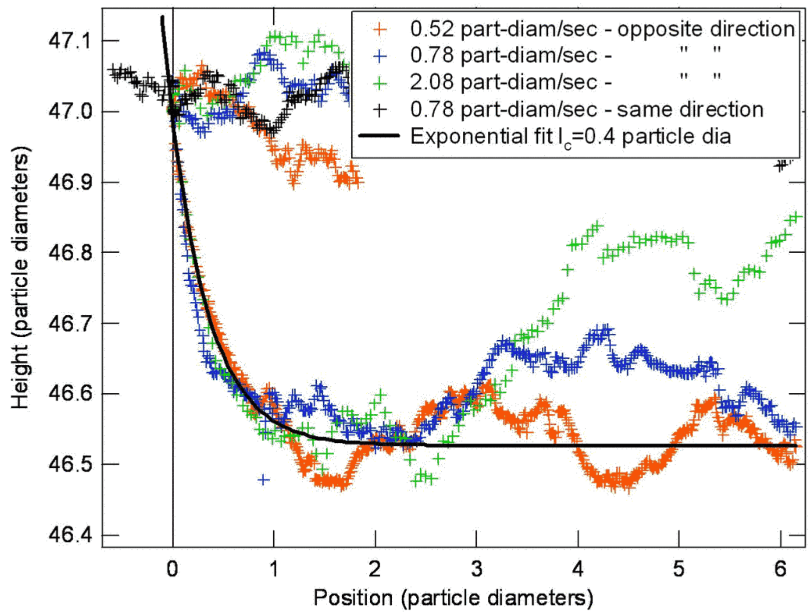
**Contact network breaks**
-> Material can compact




Imaging flow height as measure of average density

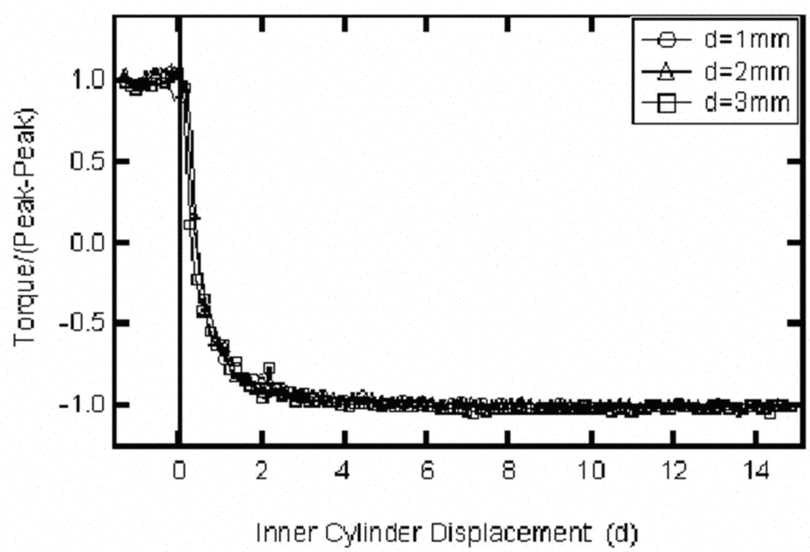


## Network breaks during shear reversal



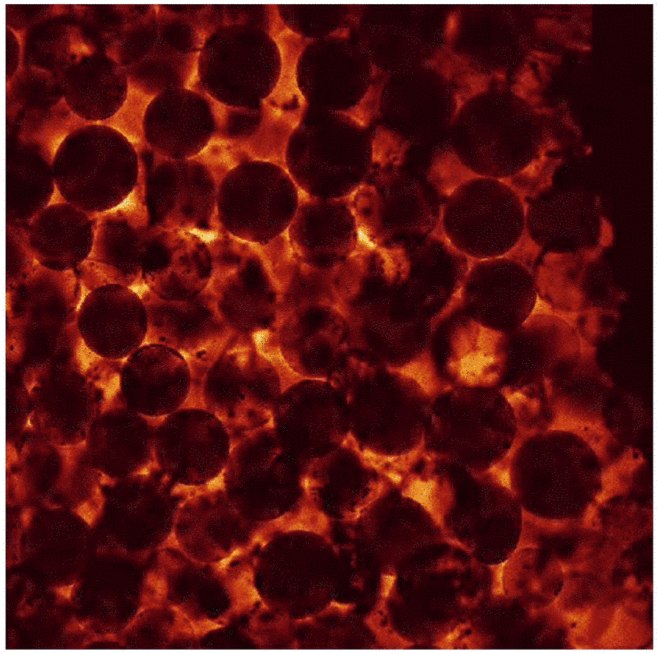

Characteristic length of compaction is about 0.5 particle diameters

## Contact Network reforms rapidly

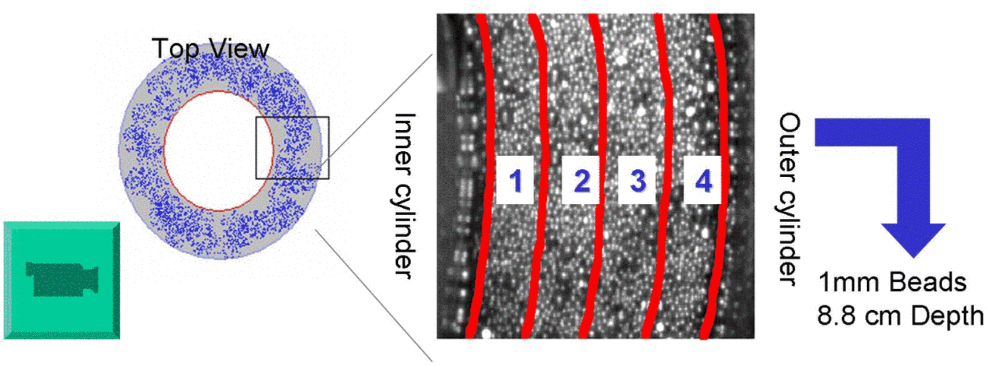



- Initial shear force smaller – scales with particle diameter
- Steady state shear force reached after ~3-5 particle diameter rotation of inner cylinder

Movie of
Shear
Reversal

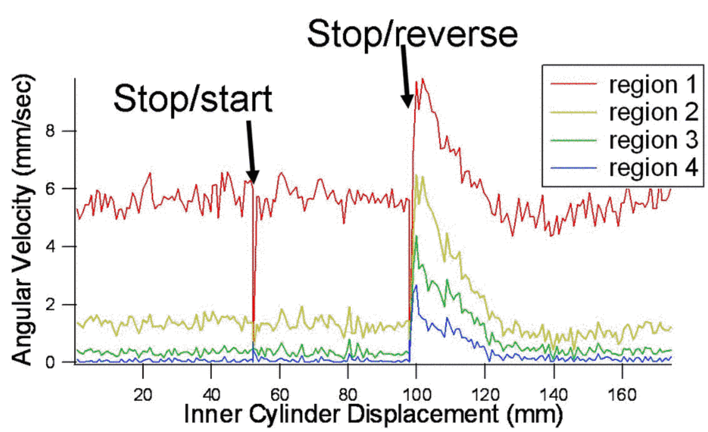


15 frames/sec; 200-500 micron diameter particles
400 microns into the sample

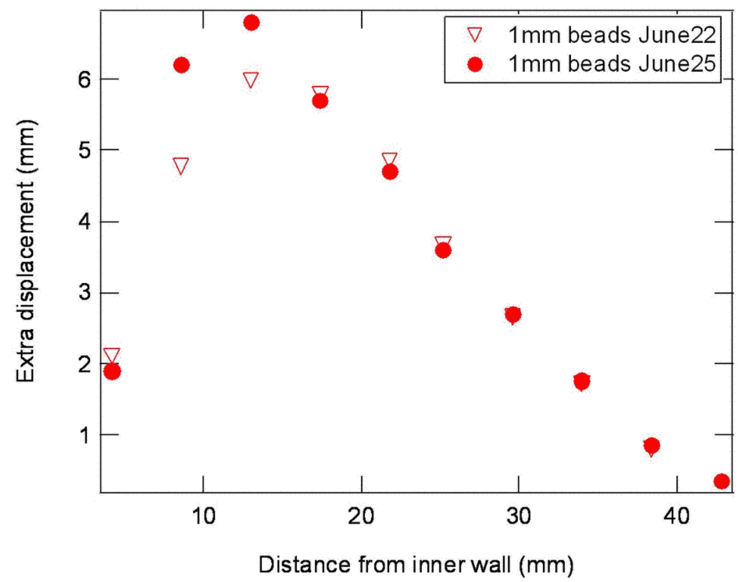



**Particle tracking on top surface:**

- Average over each region and time
- Angular velocities shown

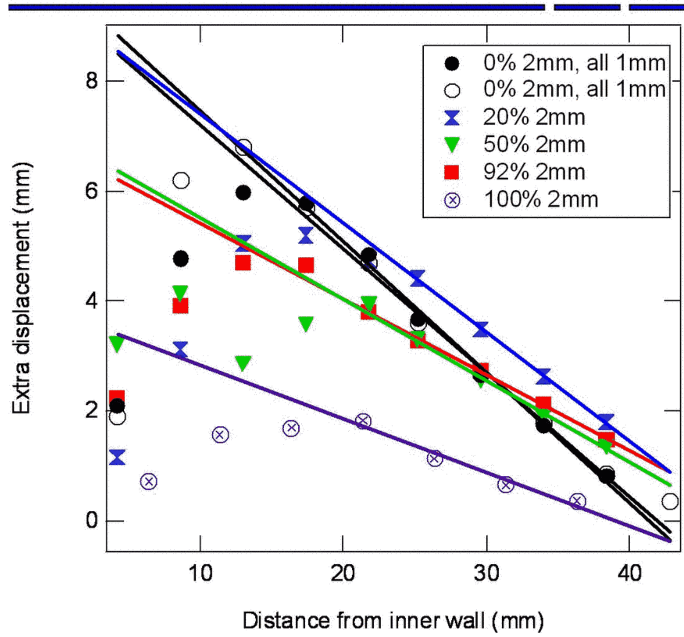


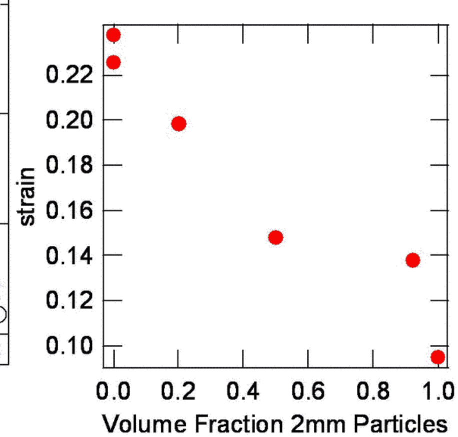
## Extra displacement of particles during start of flow




- Linear strain at the start of the flow

## Initial linear strain decreases with added large particles



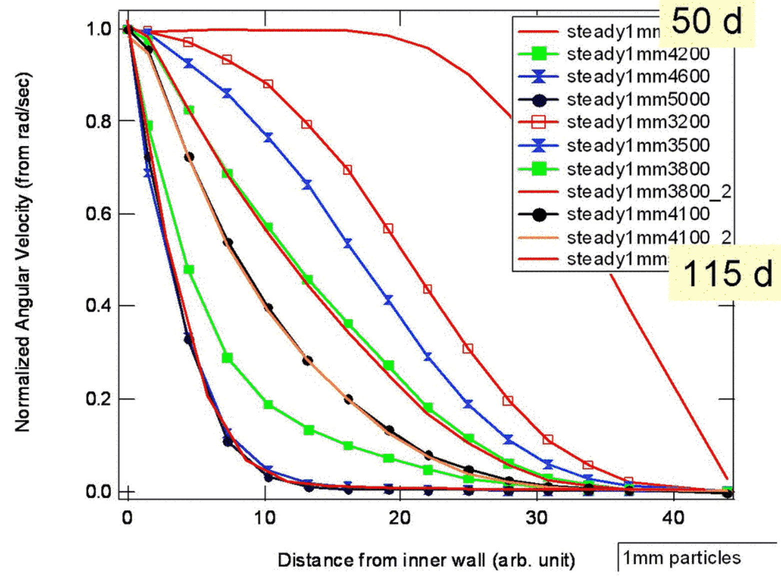




Toiya et al, to be submitted

## Does behavior during shear reversal depend on steady sheared state?

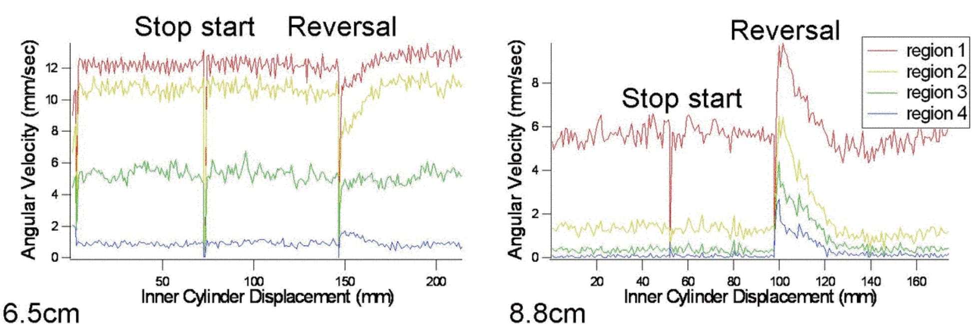
**Rough bottom connected to inner cylinder:**

Shear Band position and width depends on filling height of shear cell



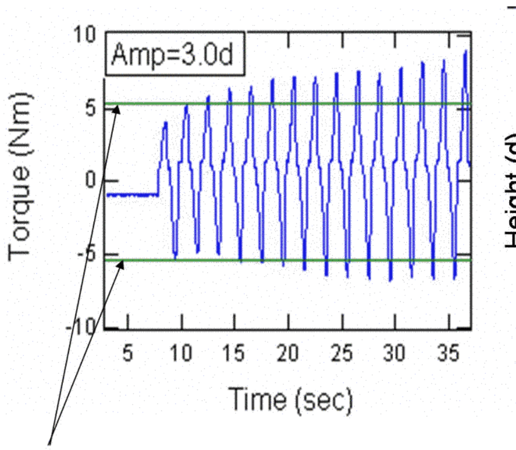

Toiya et al, to be submitted

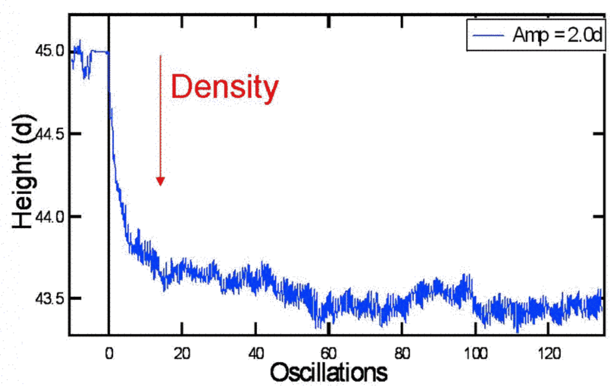
## Angular Velocity vs. Time




- No change observed when shearing started in same direction
- Reversal: Roughly linear velocity gradient for a short time

## Not yet steady state contact network

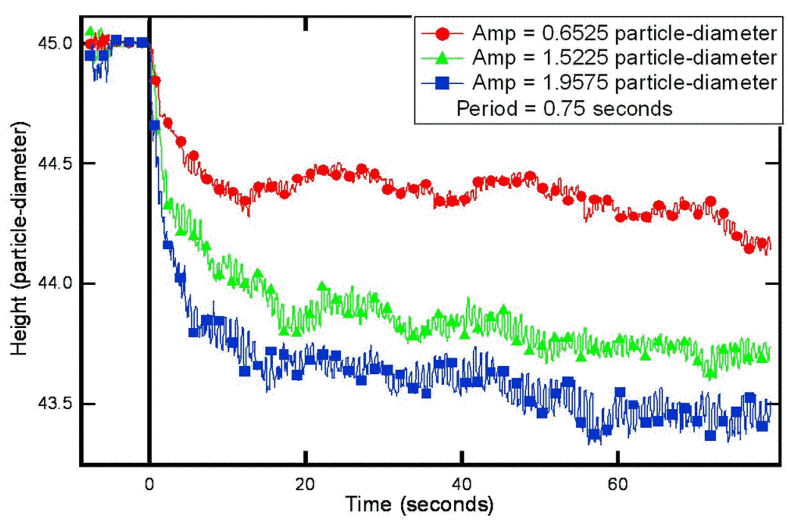



•Steady state shear torque

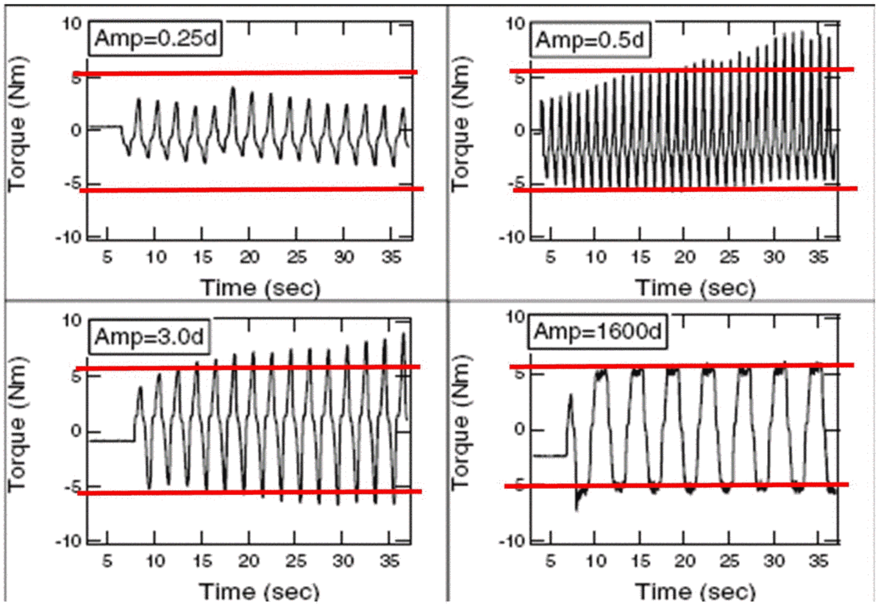
•Strengthening +compaction through oscillatory shear

Toiya et al, PRL



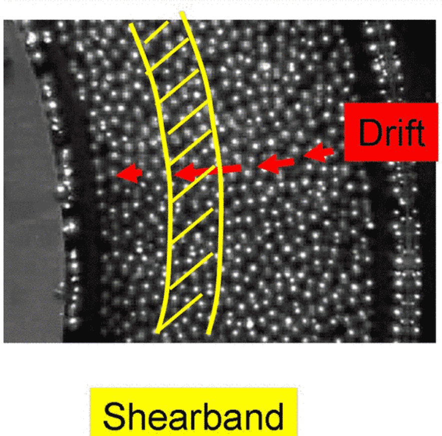

Toiya et al, PRL

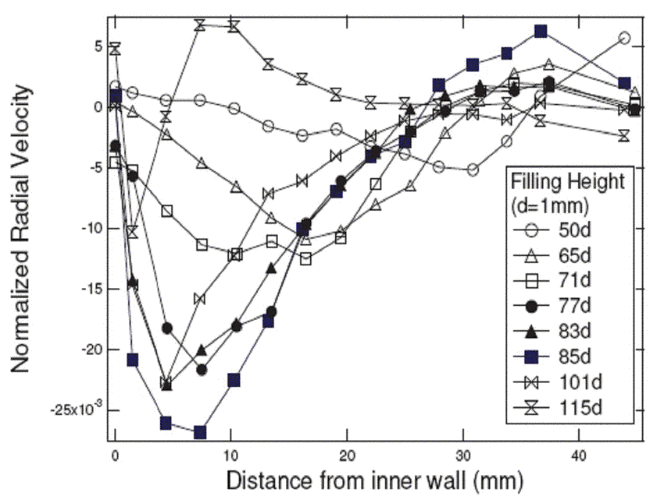
# Forces




Toiya et al, PRL

# Next “time”scale: Convection




- Position of peak radial flow ~coincides with highest shear rate – Indication of convective flow (see Grest et al KITP, Behringer 94)
- Convective flow speed appears to increase for deeper layers and wider shearbands

## Conclusions: Start of shear flow

- Shear Reversal:
  - Contact network has preferred orientation
  - Network breaks over 1d wall shear -> Compaction.
  - Steady state shear stress reached after ~3-5 d wall shear
  - Linear strain regime at reversal
    - increases with increasing width/d?
- Oscillatory Shear: Contact Network Aging
  - Network reaches "steady state" after > 50 particle dia. Shear
  - Oscillations of smaller amplitude lead to strengthening
- Steady Shear:
  - Convective flows increase with increasing depth
  - Convection leads to segregation

## *ACKNOWLEDGEMENTS*

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**Publications:** W. Losert and G. Kwon, (2002)
M. Toiya, J. Stambaugh, W. Losert, PRL 93, 088001 (2004).
Friedmann, et al J. Geophys. Res. 108, No. B8, 2380 (2003).
M. Toiya et al, to be submitted

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