High Speed Particle Imaging of Particle Flow Fields

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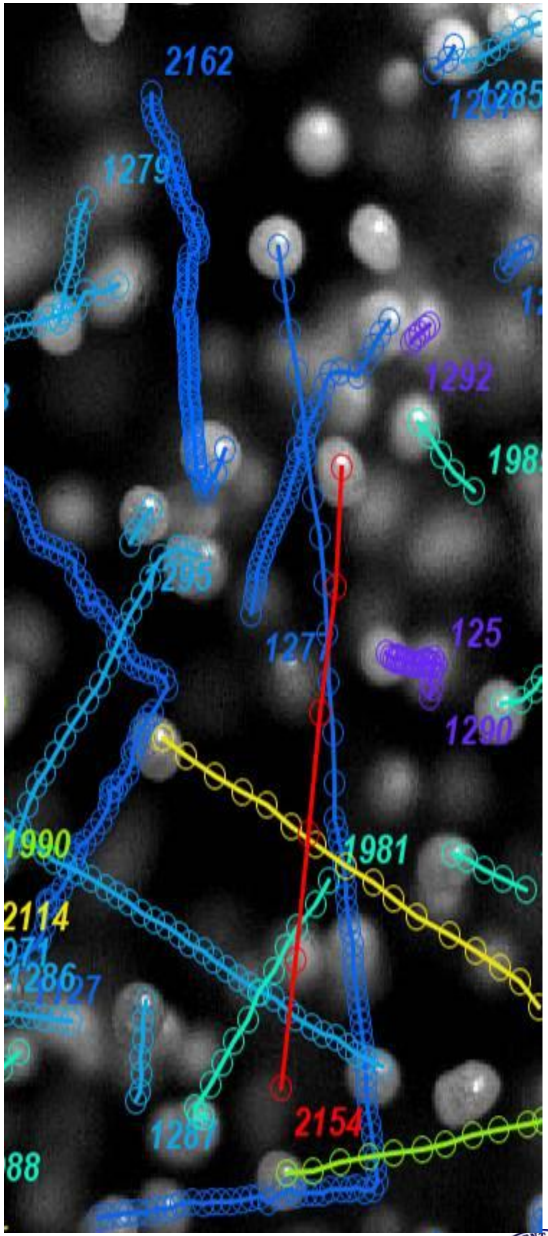


High Speed Particle Imaging of Particle Flow Fields

The goal of this project is to see and measure particle flow fields of high particle concentration, including individual particle behavior inside particle flow fields.

Usually flow visualization is the first step in studying a flow phenomenon. In the case of dense particle flows, flow visualization is lagging other efforts because dense (of high particle concentration) particle flow fields are exceptionally difficult to visualize. Even at moderate concentrations, the flow fields are opaque. Particles can be abrasive or cohesive. Very intense illumination is often required because exposure times for small particles are ~1 microsecond.

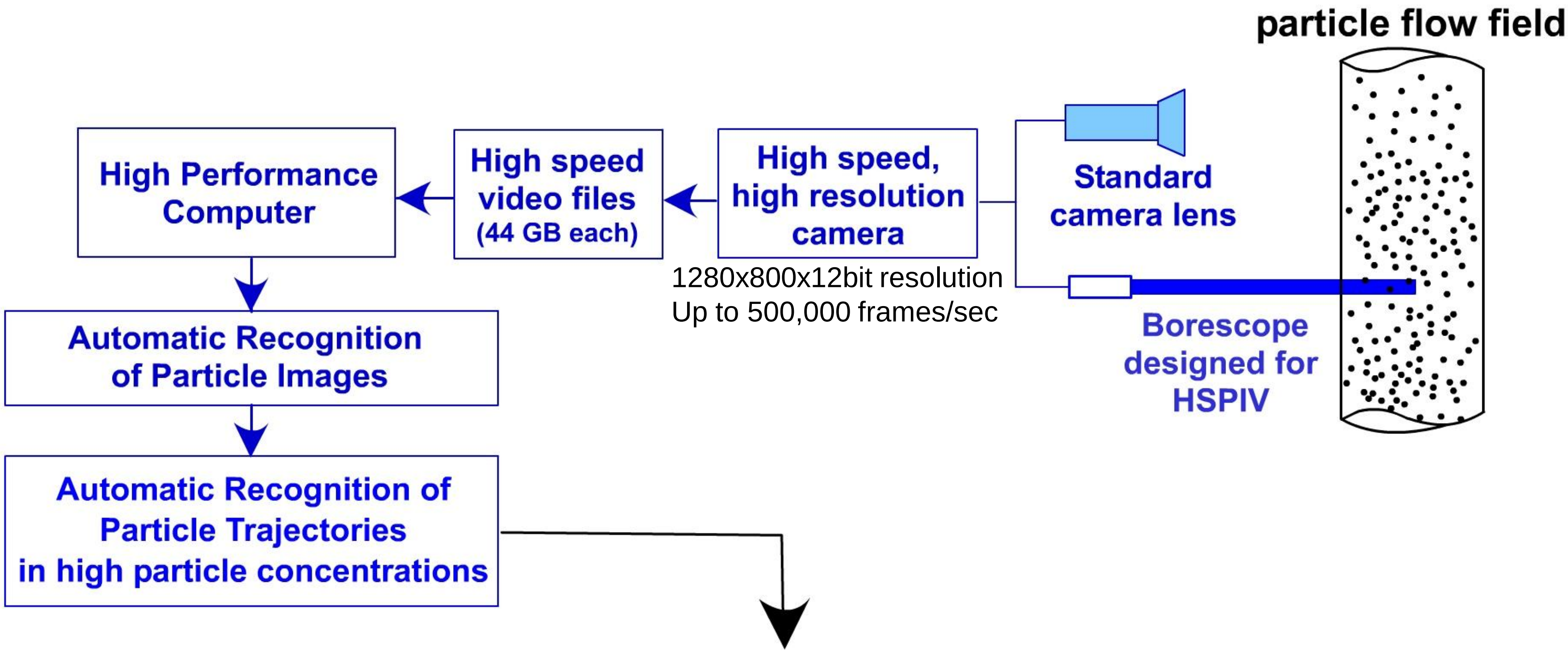
Technologies are becoming available that make possible high speed visualization of many dense particle flow fields. In the past decade non-laser light sources have become much brighter and sensitivity of high speed cameras has improved. We have designed custom borescopes to probe into dense flow fields.

High Speed Particle Imaging of Particle Flow Fields

Particle flow phenomena that we have successfully visualized and measured:

- *Dense flow fields in CFB risers*
- *Fluctuating component of velocity and Granular Temperature*
- *Clustering behavior in*
    - *fluidized beds,*
    - *the freeboard region above a fluidized bed*
    - *CFB risers*
- *Jet injection and jet bypassing in fluidized beds*
- *Downward, pulsatile packed bed flow field in a CFB standpipe*
- *Flow over probes: fiber-optic probes, LDV, piezo probes*
- *Full field mapping in a small fluid bed for validation of DEM CFD*

High Speed Particle Imaging (PIV) System

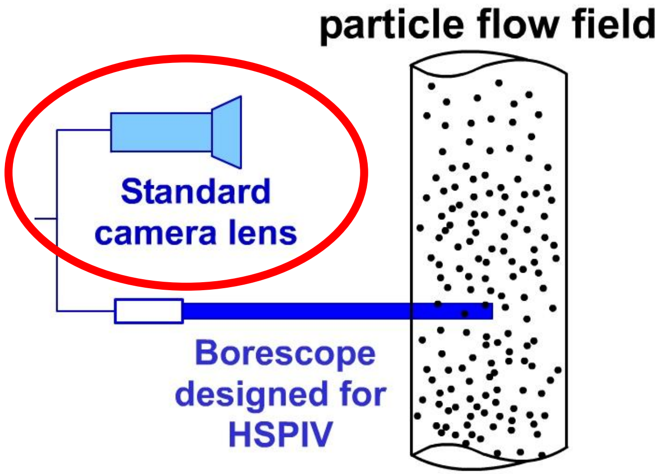


Data describing particle flow with high accuracy and sample rates

Simultaneous measurement of individual particle velocity, particle trajectories, particle concentration.

Patent application no. 12765317, April 2010. “Automatic particle trajectory recognition in high concentration particle flows by a candidate tree search method.”

High concentration particle flows: *what the human eye sees*



Standard video at 30 frames/sec, 1/30 second exposure with standard lens. Flow field in riser of the NETL CFB

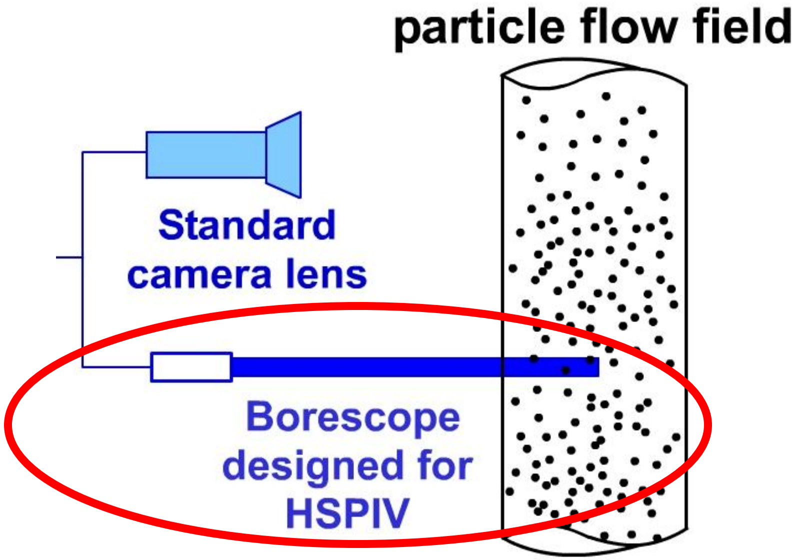
High concentration particle flows:
High speed video at 1000 frames/sec

High speed video

Human eye / standard video

High concentration particle flows:
seeing inside an opaque flow field with a borescope

We have worked with Gradient Lens Corp to design custom borescopes for seeing individual particle motion inside particle flow fields.
Example high speed video of individual particle motion inside the riser of the NETL CFB.



Borescopes do cause some flow disturbance, but we know of no other way to see inside dense particle flow fields. In CFB risers, we usually do not observe significant flow disturbance. We plan to assess the degree of disturbance with high speed PIV and CFD.

Data Produced by High Speed PIV: Automatic analysis

A typical high speed video for PIV in a CFB riser:

- 44 Gbytes
- 100,000 video frames
- 1-5 million particle images

The 1-5 million particle images must be automatically recognized and tracked through video frames. We have developed software to automatically recognize and track particle images in high speed videos. The software algorithms avoid the computational explosion caused by the "correspondence ambiguity" problem of multiple object tracking.

In April of 2010 we filed a patent application (App. No. 12765317): "Automatic particle trajectory recognition in high concentration particle flows by a candidate tree search method."

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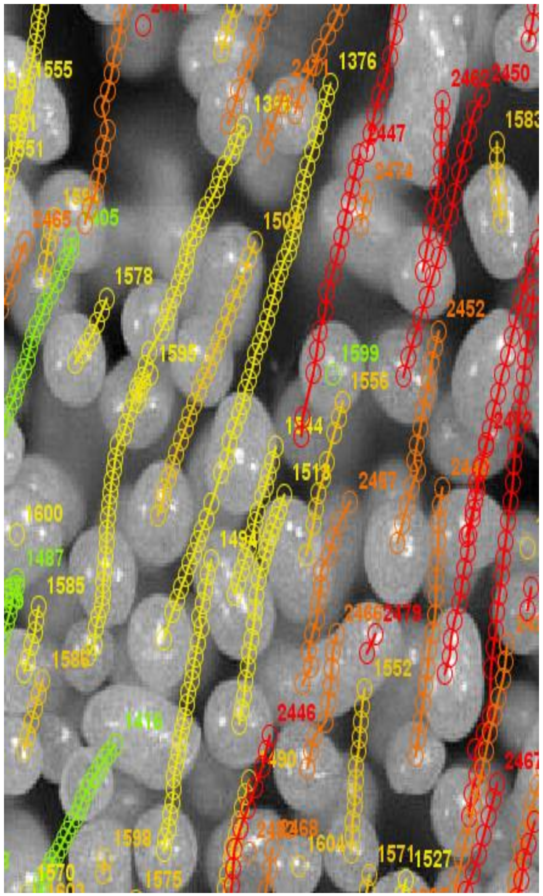
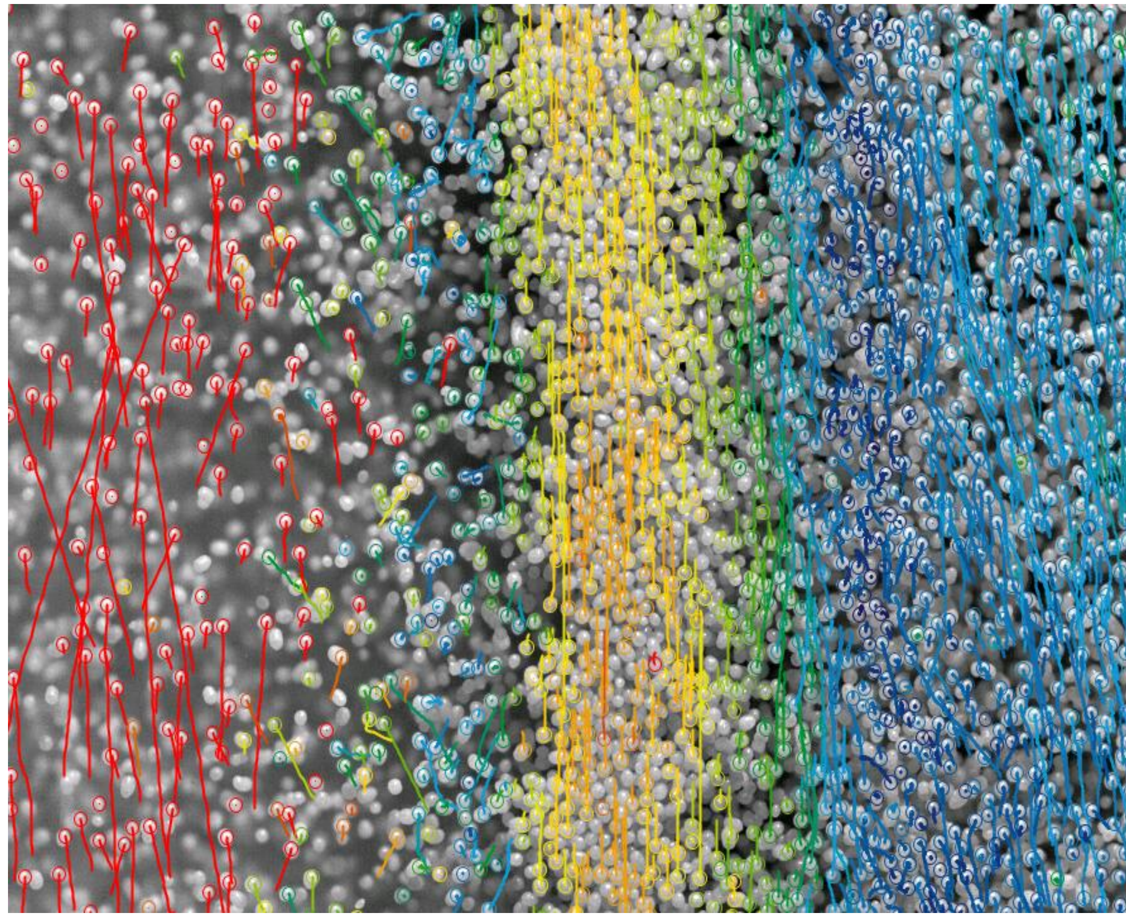
Two Types of High Speed PIV Measurements: "Point*" Measurements and Large Area Mapping

Small area "point" measurements:
Measurement area ~ 1-5 mm

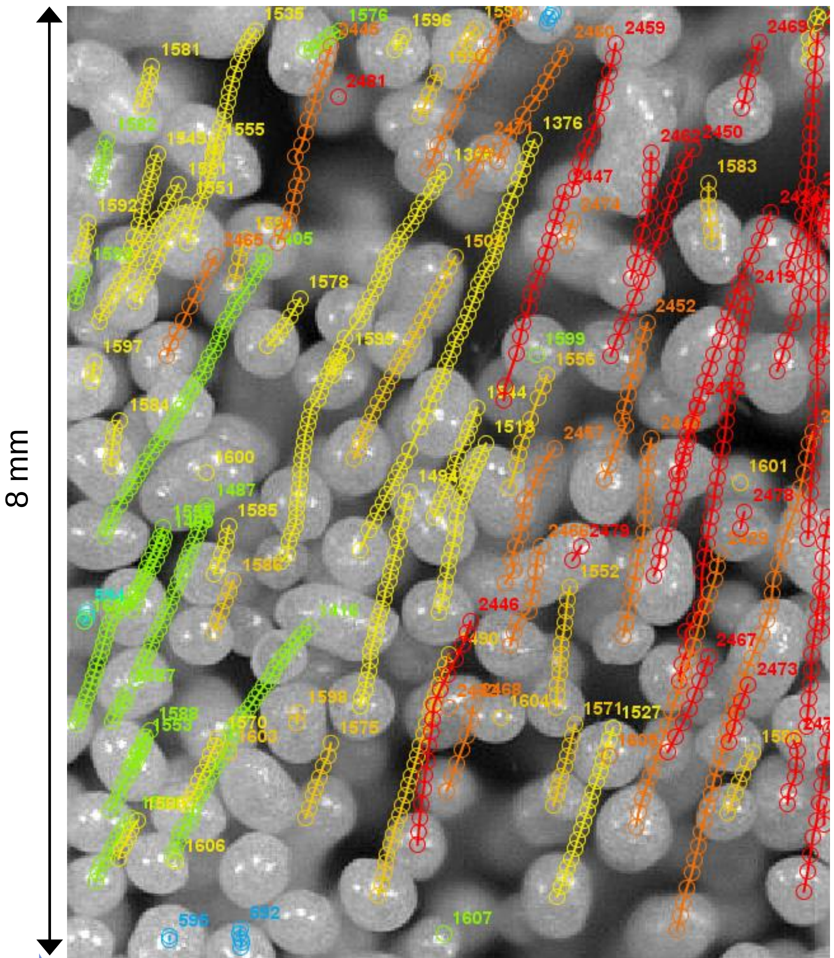


Large Area Flow Mapping:
Measurement area ~ 10 cm



** "Point" means that the measurement area is small enough that there are not significant time-averaged gradients over the area.*

High Speed PIV Measurements:
Example point measurement of particle-wall slip boundary condition



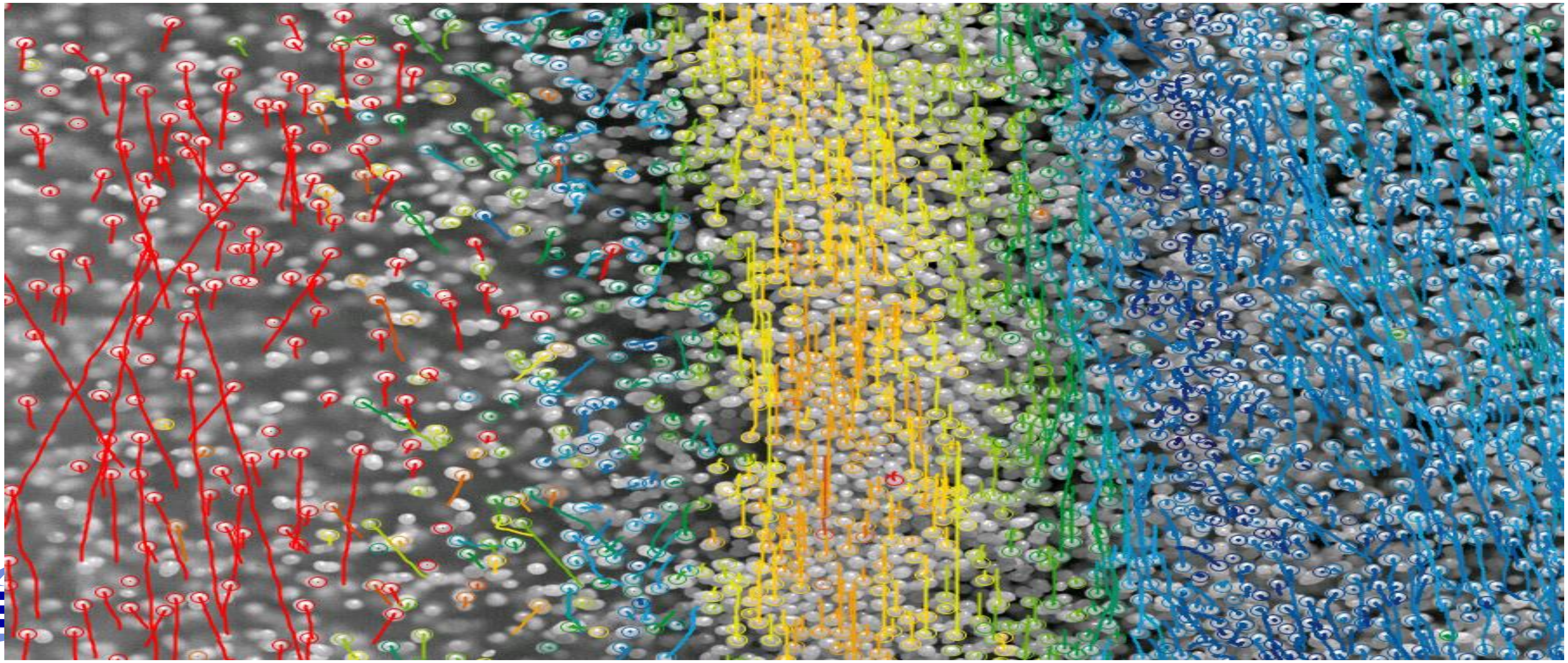
Examples

- Close-up of particle flow on the wall of the NETL CFB riser
- Recognized and tracked trajectories

Data Produced by HSPIV: Large Area Flow Mapping

- Acquired through a transparent wall
- Dimensions of sample area ~100 to >1000 particle diameters
- Measured parameters:
  - 2D particle trajectories over long periods
  - 2D velocity along each trajectory
  - 2D map of velocity for each video frame
  - 2D map of concentration for each video frame

Example: [Original hs video] [With analyzed trajectories]



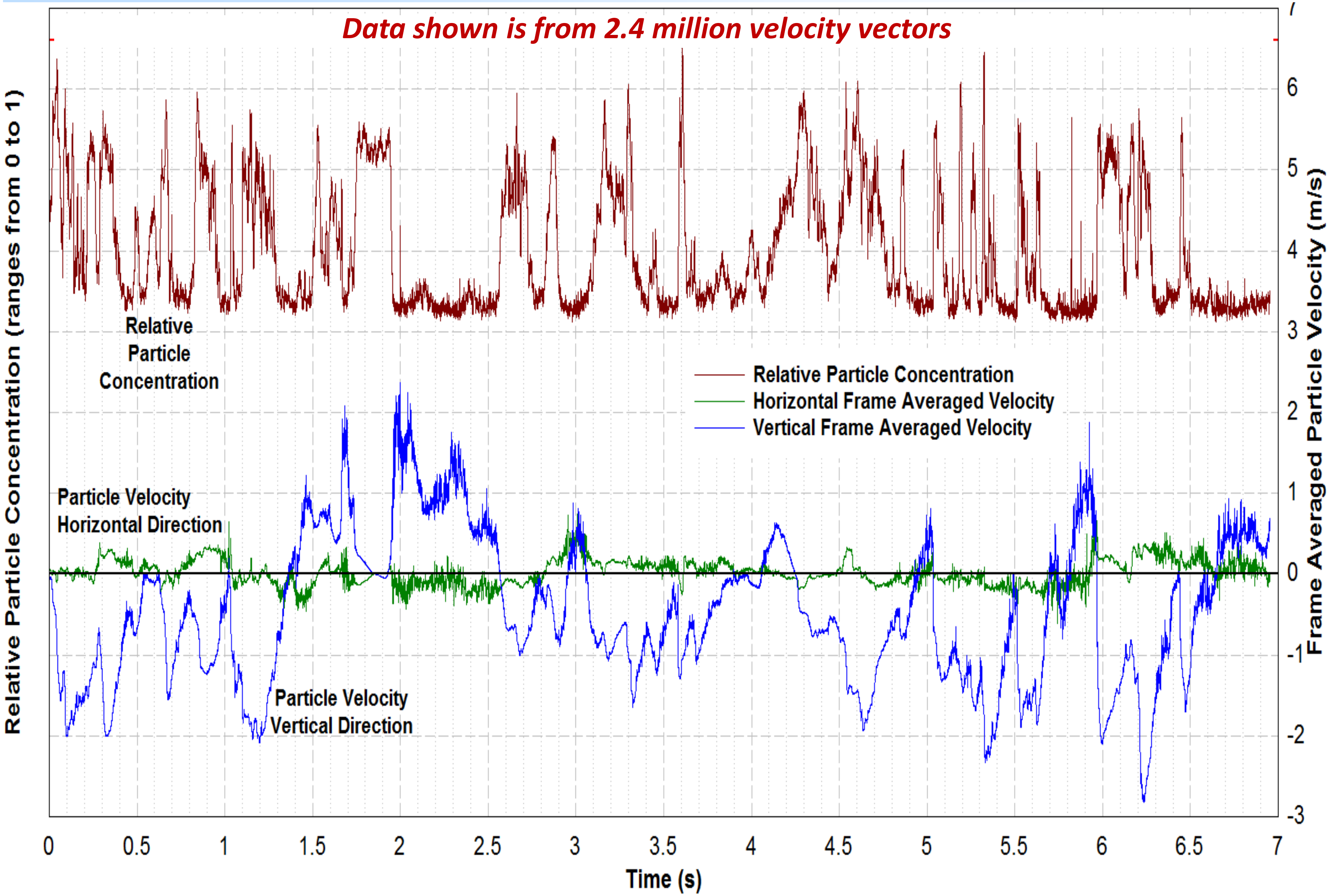
Data Produced by High Speed PIV

- **Data acquired for point measurements:**
  - ***Instantaneous 2D velocity; inc. fluctuating component***
  - ***Relative particle concentration***
  - ***Particle-particle collisions automatically detected***
  - **Particle rotation (manual analysis only)**

- **Data acquired for large area mapping:**
  - ***2D velocity maps***
  - ***Relative particle concentration maps***

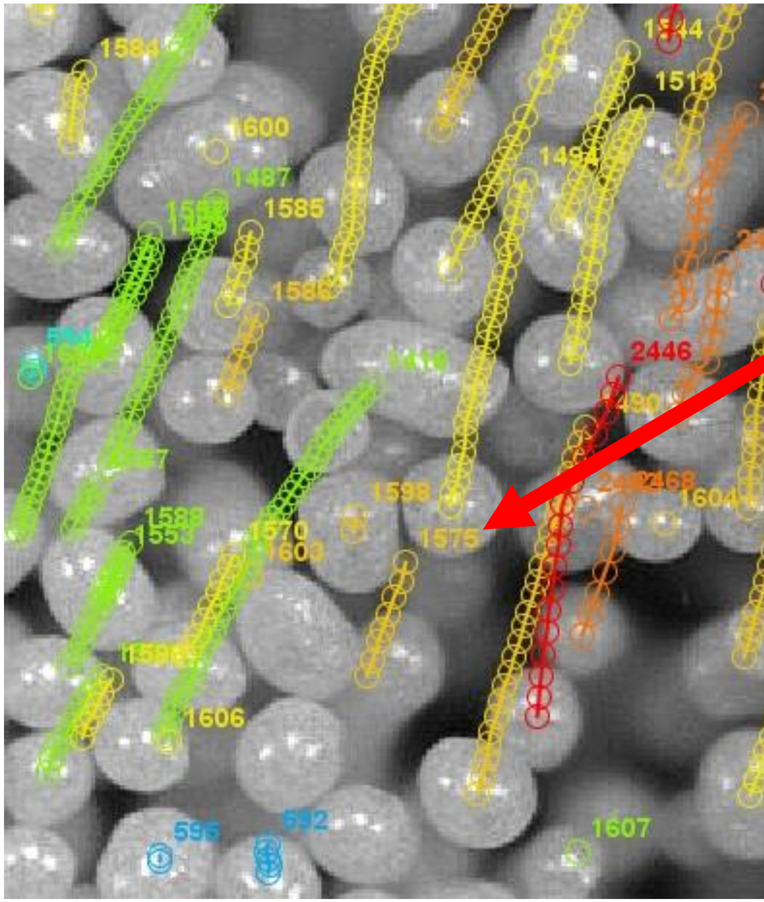
- **Measurement uncertainty for particle velocity is very low:**
  - **<1% for measurements through transparent walls and**
  - **~5% through a borescope**

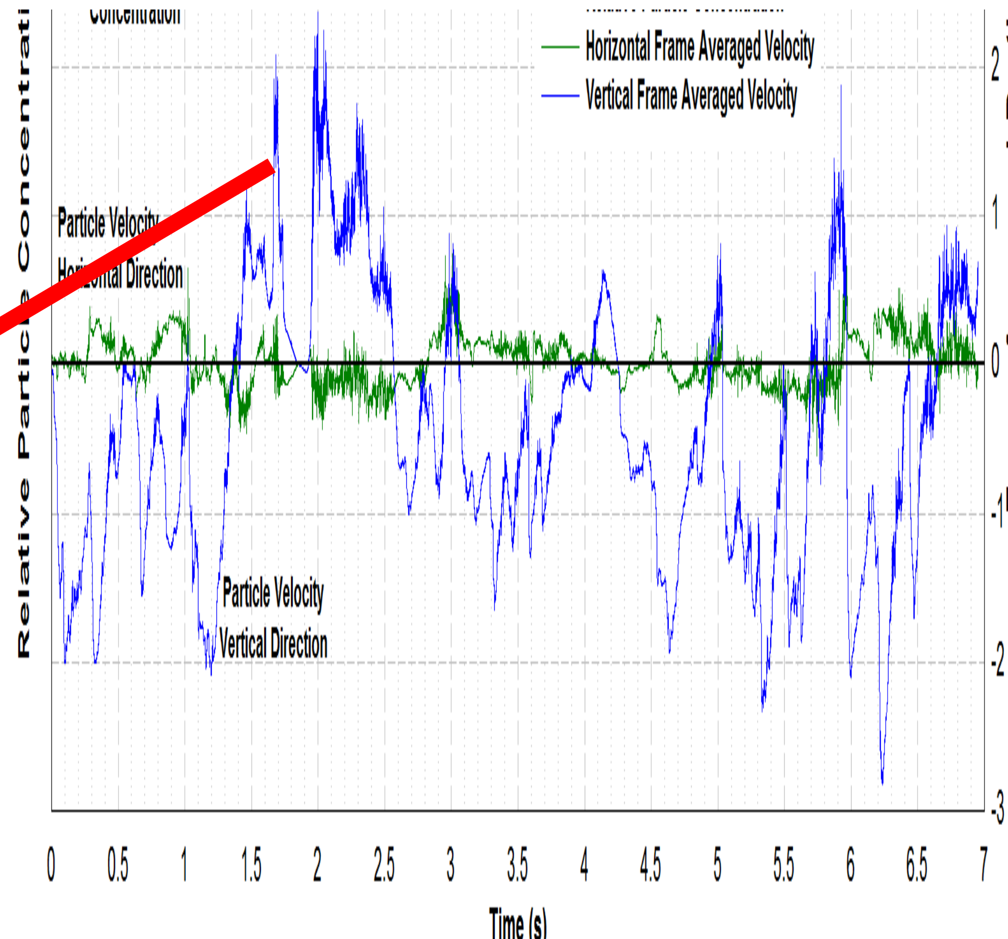
hsPIV Measurement of Local-Avg'd Particle Velocity and Concentration
NETL 12" riser: 750 micron HDPE; superficial gas velocity = 6.6 m/s, solids flux = 20 kg/m2/s
12,500 frames/sec ; 4 μs exposure



Unique Advantages of High Speed PIV:

HSPIV is the only measurement technique that allows each data point to be reviewed in a high speed video showing particle motion that generated the data point.





Selected Initial Results from High Speed PIV Measurements

- Comparison with other measurement techniques: LDV and Fiber-Optic Probes
- Granular Temperature
- Unsteady jet behavior in CFB risers
- Clustering behavior in fluidized beds, above fluidized beds, and in CFB risers

Selected Initial Results from Point Measurements
Comparison with Other Measurement Techniques

- High speed PIV has high sample rates for particle velocity, in the range of 0.1 to 1.0 million velocity vectors per second
- The high sample rates resolves high frequency components of the pointwise particle velocity signal. We see significant frequencies in the range of 1 – 5 KHz for 70 micron FCC and 100 – 500 Hz for 750 micron HDPE
- Other techniques, e.g., fiber-optic probes and LDV, may have sample rates too low (~ 100 Hz) to detect the full frequency spectrum of velocity signal

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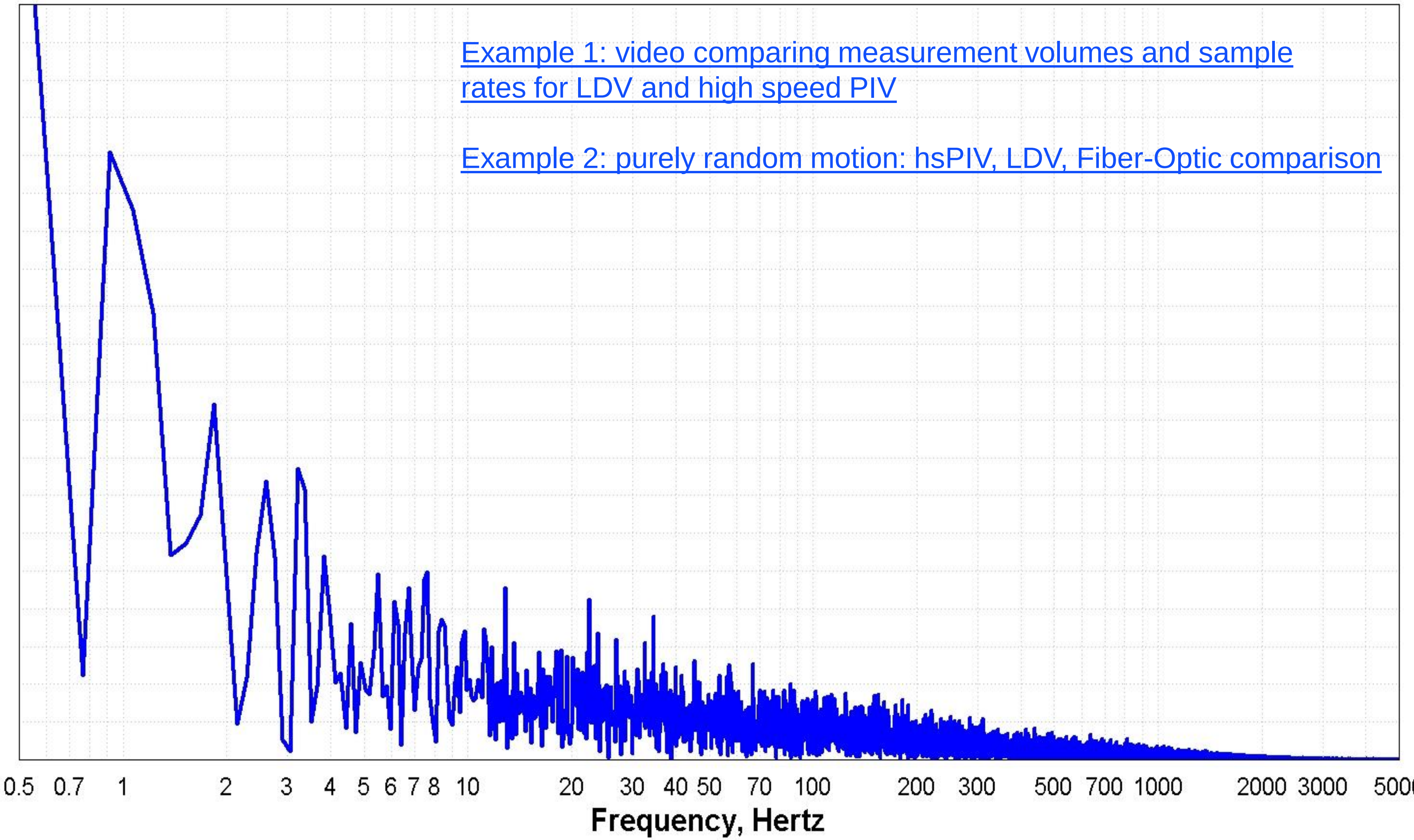
Frequency Components of Local Mean Velocity: FFT of Particle Velocity

PSRI 8” Riser; 70 micron mean FCC; gas = 18.3 m/s ; solids flux = 400 kg/m2/s

Example 1: video comparing measurement volumes and sample rates for LDV and high speed PIV

Example 2: purely random motion: hsPIV, LDV, Fiber-Optic comparison

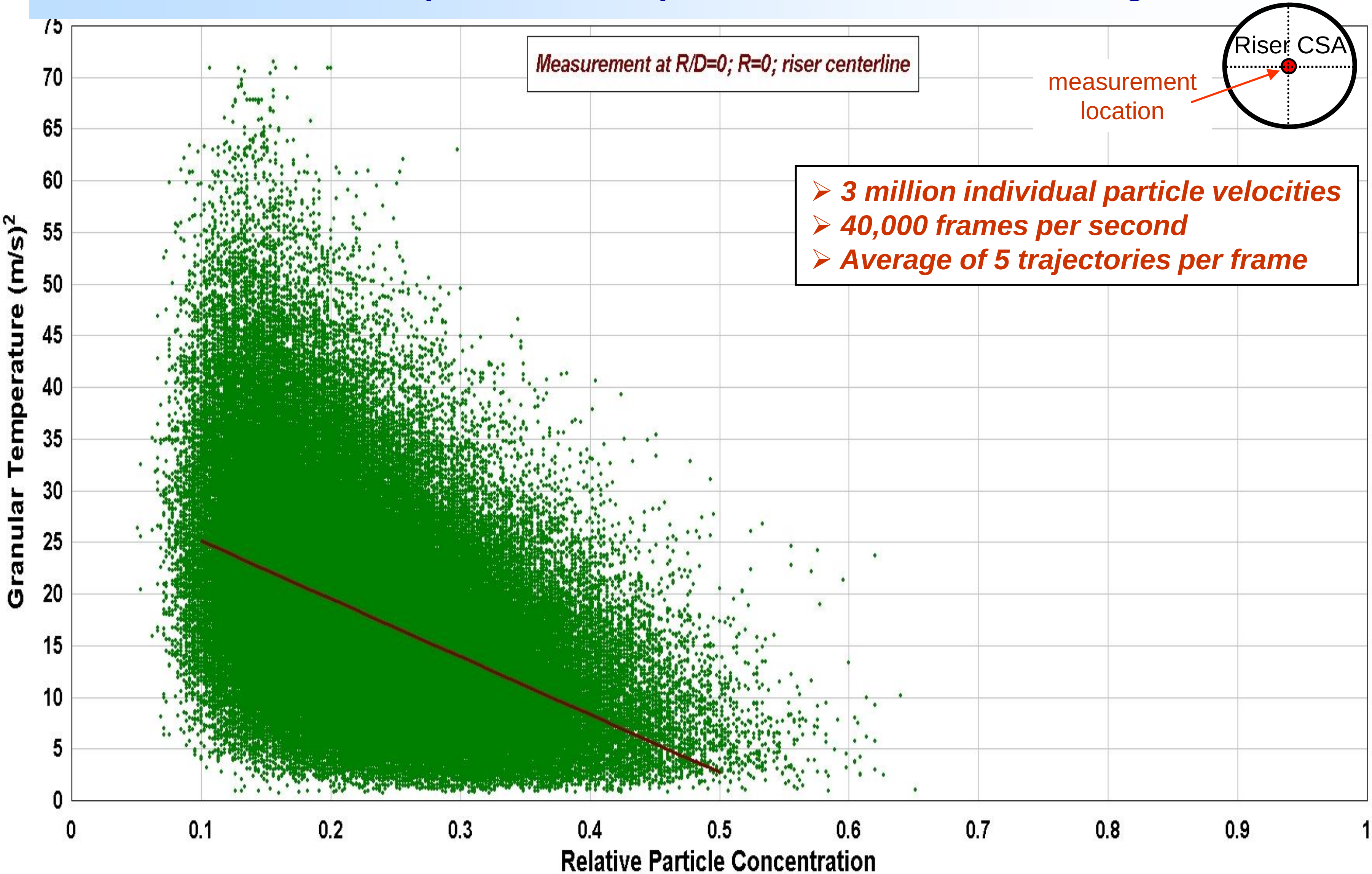


Selected Initial Results from High Speed PIV Measurements: Granular Temperature

- Low measurement uncertainty and high sample rates produce accurate measurements of the fluctuating component of particle velocity.
- This enables accurate calculation, perhaps for the first time, of important modeling parameters, for example Granular Temperature

Granular Temperature in PSRI 8" Riser

70 micron FCC; Gas superficial velocity = 18.3 m/s; solids flux = 380 kg/m²/s



Granular Temperature in PSRI 8” Riser

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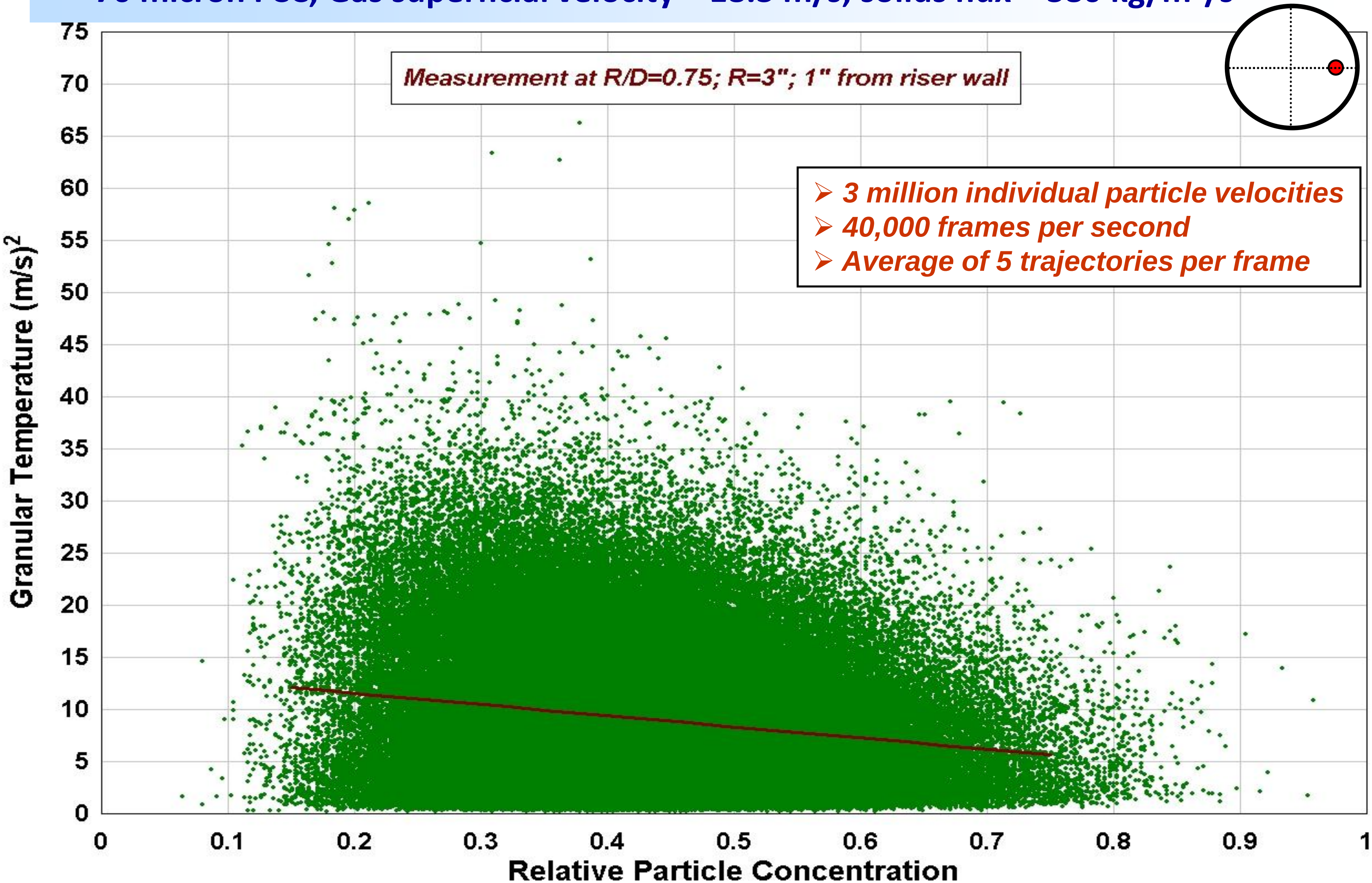

Granular Temperature in PSRI 8" Riser
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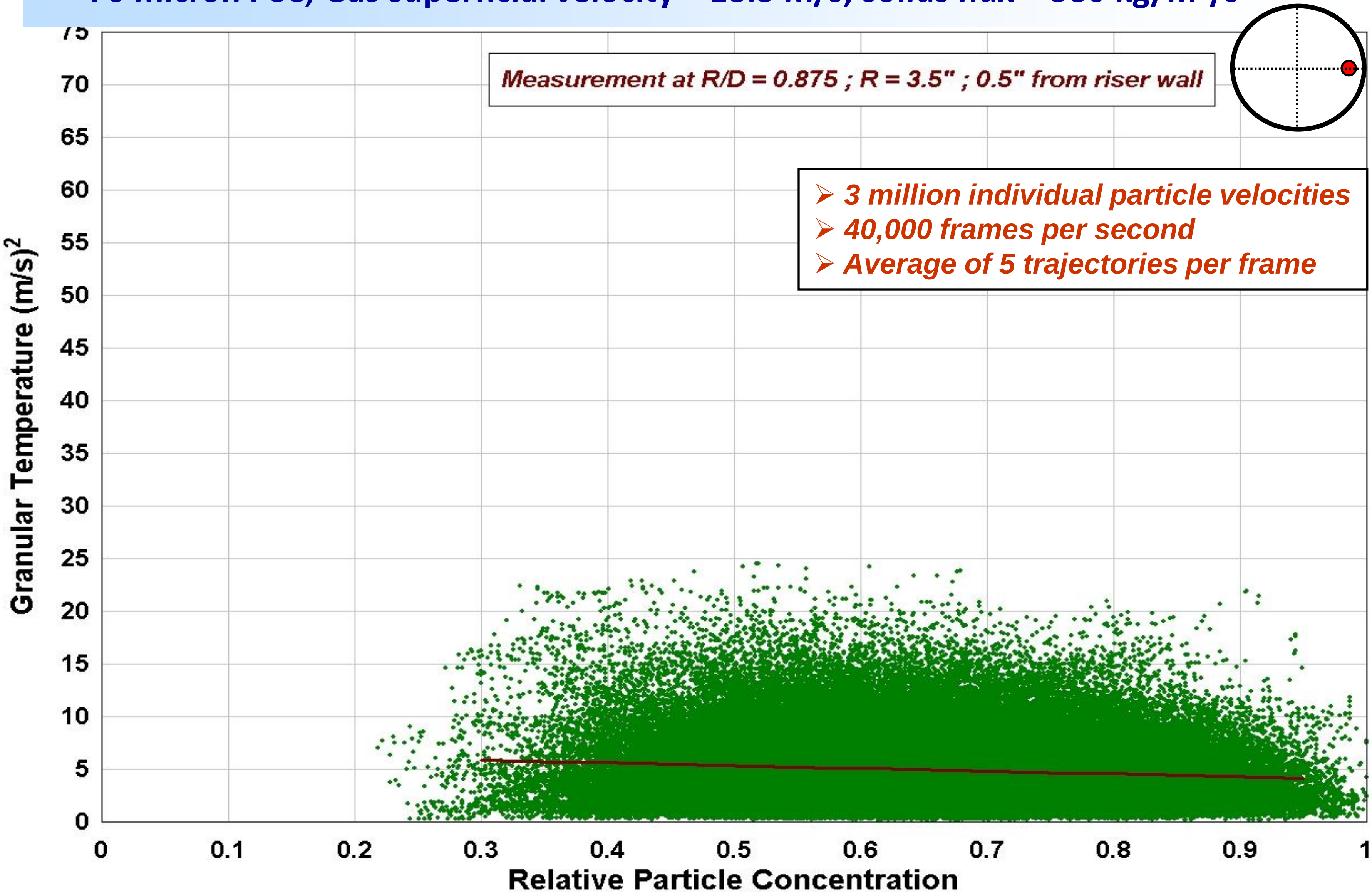

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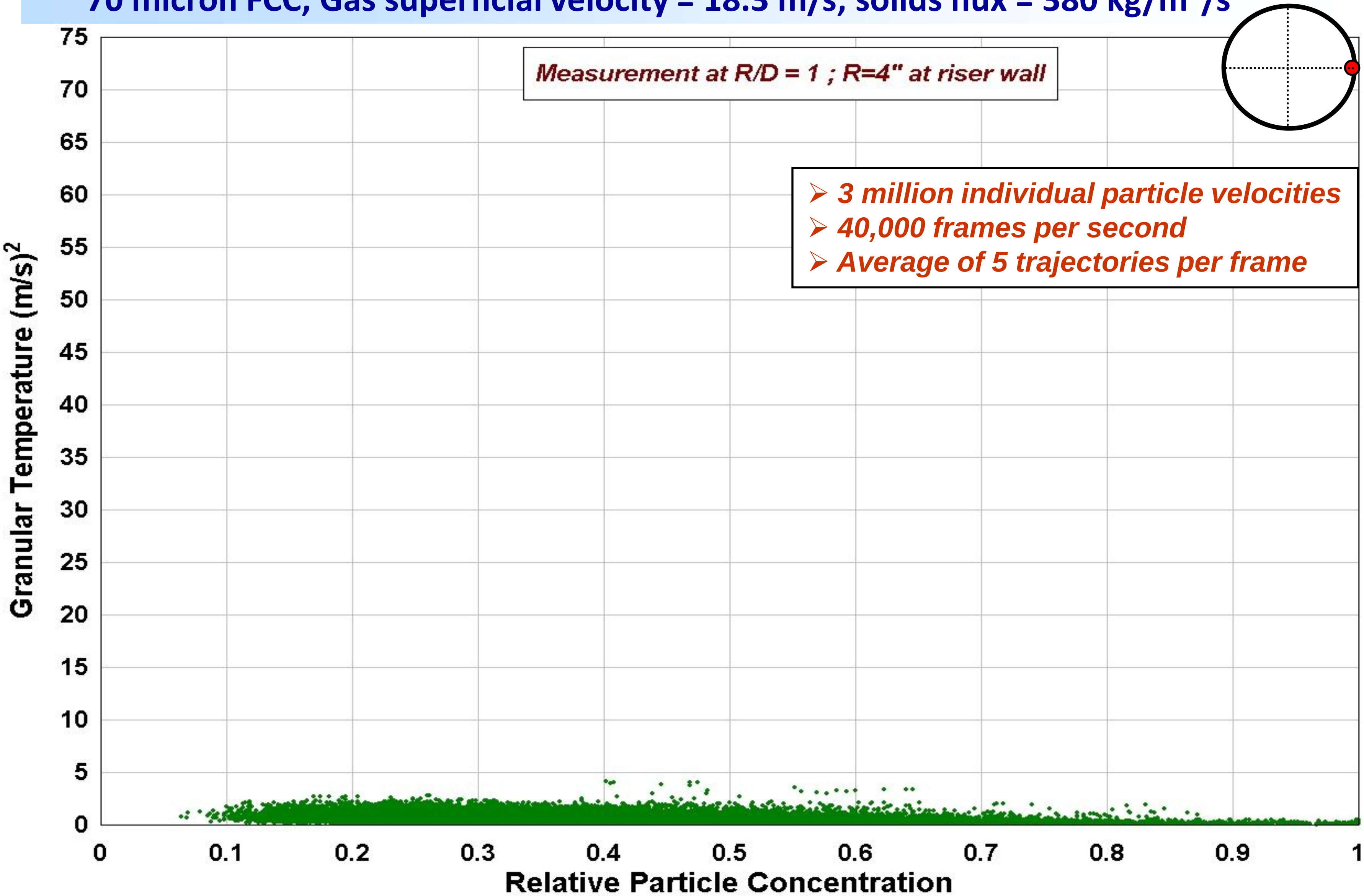

Selected Initial Results from High Speed PIV Measurements: Dr. Gopalan: Higher Order Analysis and Comparison with MFIX

This afternoon Dr. Gopalan will discuss higher order analysis of high speed PIV data

- Decomposition of velocity signal to separate frequency components caused by clusters from the random fluctuating component
- Calculate of modeling parameters like Granular Temperature, distributions (RMS) of local mean velocity, strain rates
- Comparison of hsPIV results with MFIX

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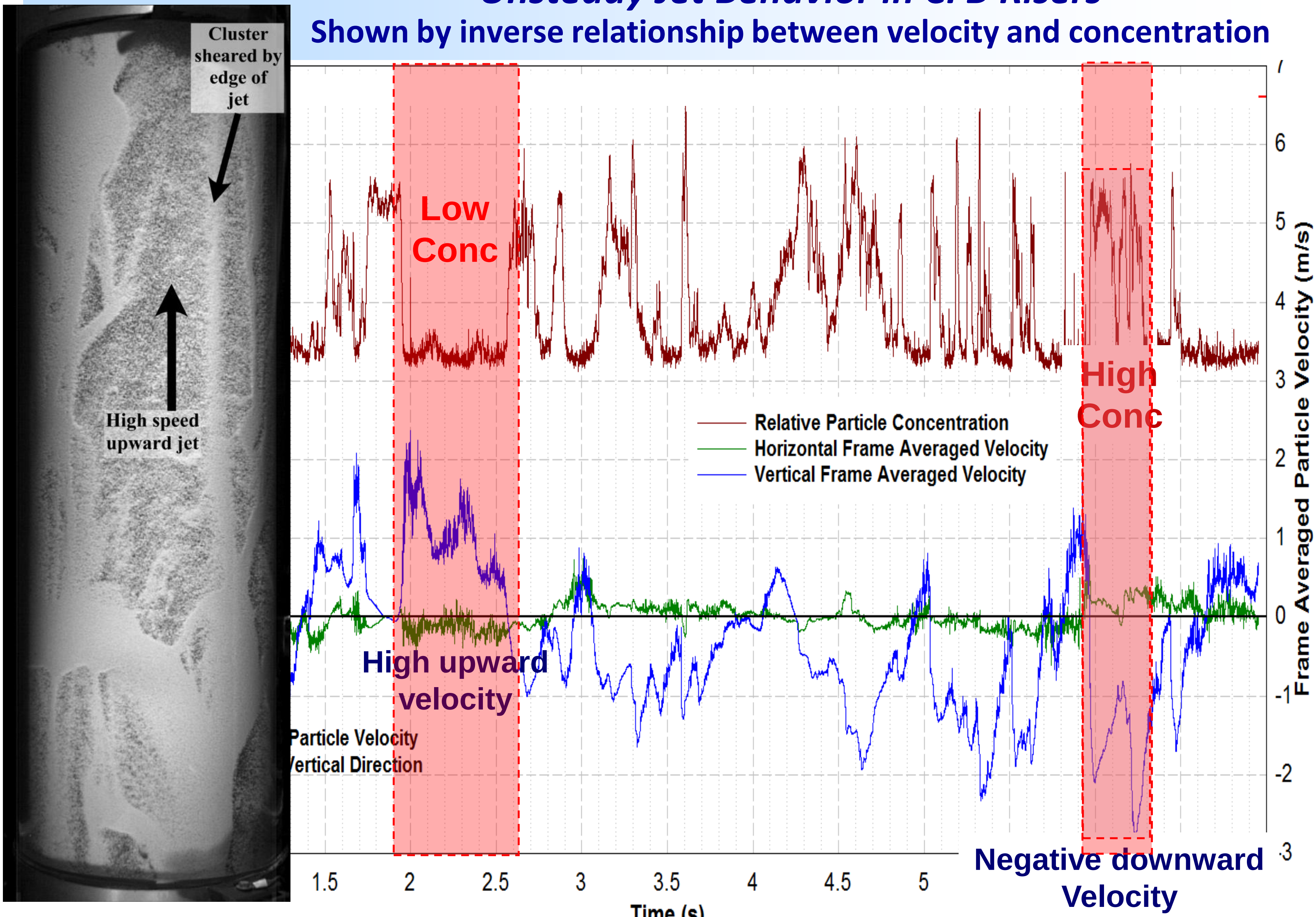
Selected Initial Results from Point Measurements: *Unsteady jet behavior in CFB risers*

- Flow is CFB risers is driven by high speed “jets” of low particle concentration
- Often more than one jet is observed
- Jets wander from one location against the riser wall to another
- When a jet moves away from an area, the area is filled with large, dense clusters with low velocity (often negative velocity)

- The “core-annulus” behavior is only a time-averaged behavior; it is not seen in real time

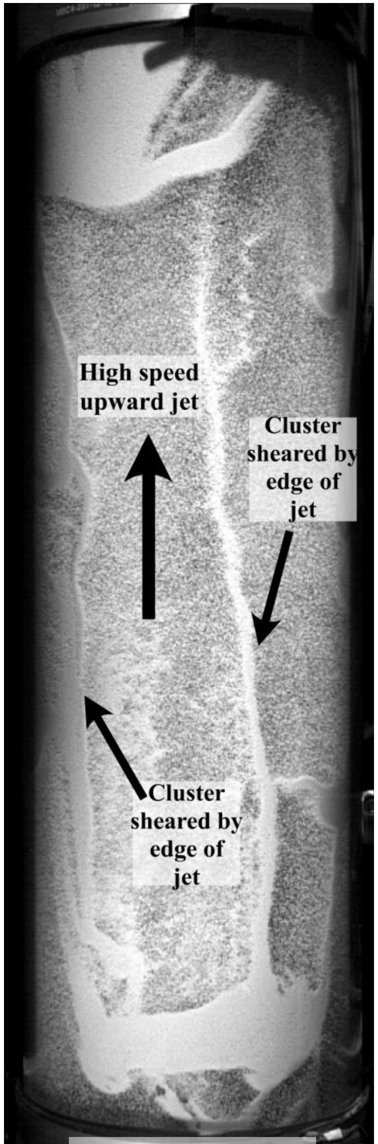
Unsteady Jet Behavior in CFB Risers

Shown by inverse relationship between velocity and concentration

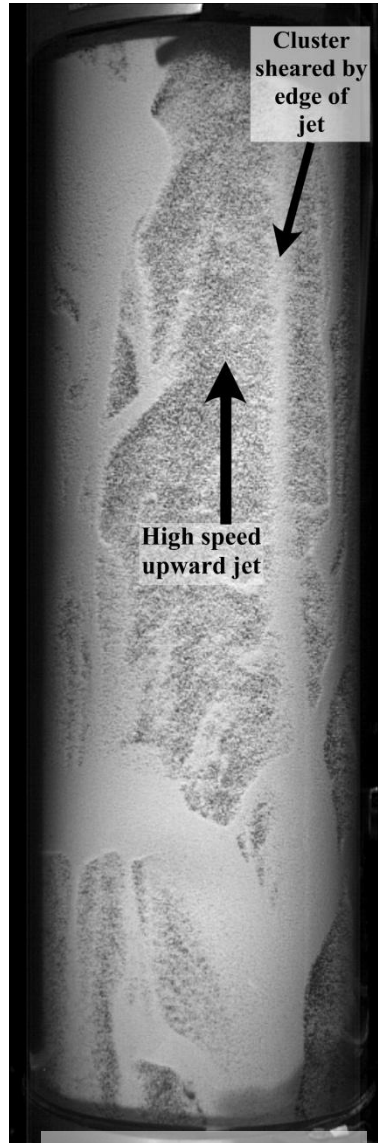


Unsteady Jet Against Riser Wall and Clustering Behavior

NETL Riser with 750 micron HDPE Particles



Low conc.

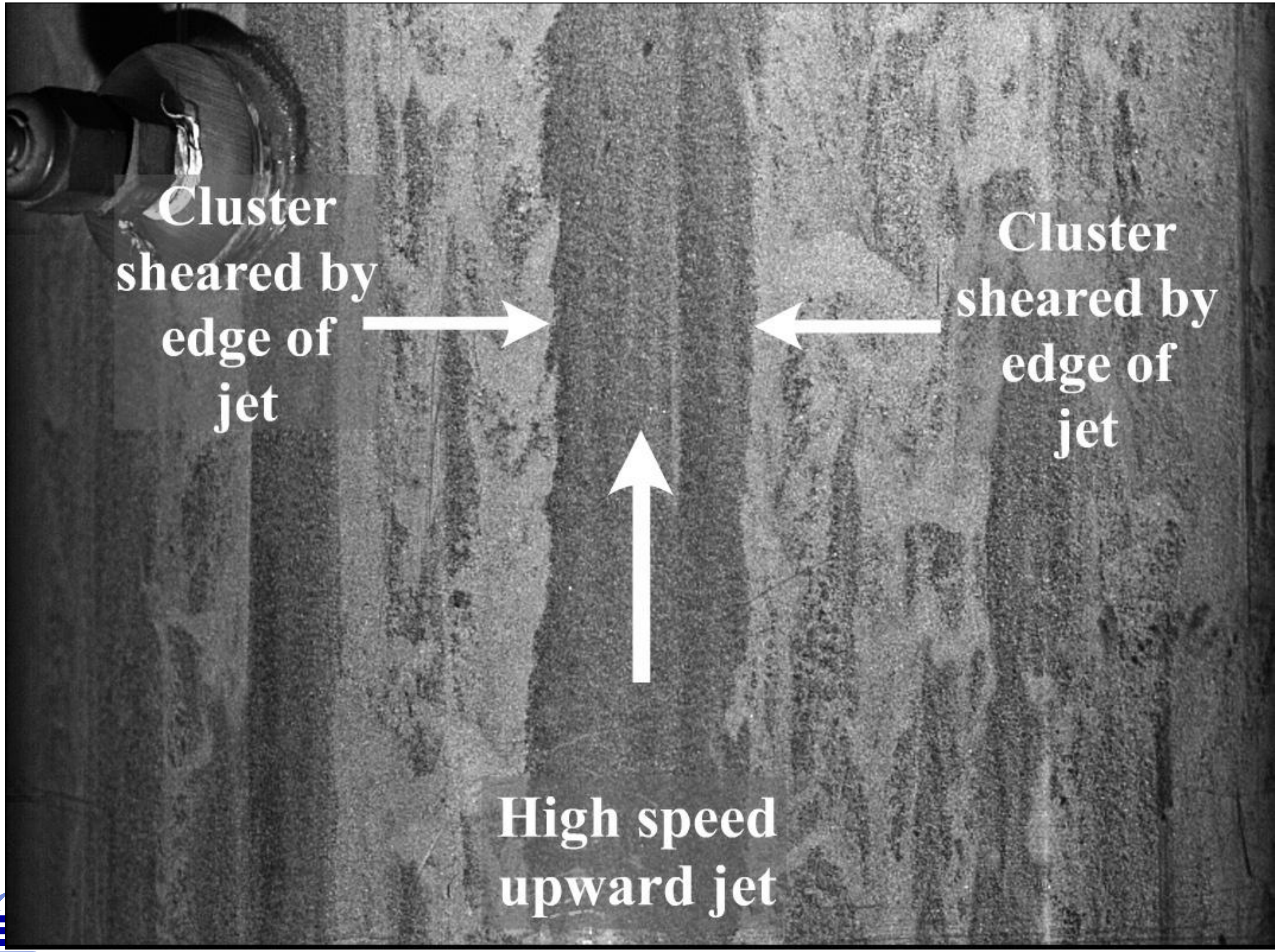


medium conc.

high conc.

3.5 ft ; 3.5 pipe diameters

PSRI 8" Riser with 70 micron FCC
Unsteady Jet Against Riser Wall and Clustering Behavior



Particle Clustering Phenomena in/above Fluidized Beds and in CFB Risers

- **We have used high speed PIV to observe that clusters in and above fluidized beds (PSRI Entrainment Research Unit) and in CFB risers (NETL and PSRI)**

- **The physical characteristics of clusters are very different in fluid beds and risers**

- **Yet models for CFB risers are based on cluster data from fluidized beds**

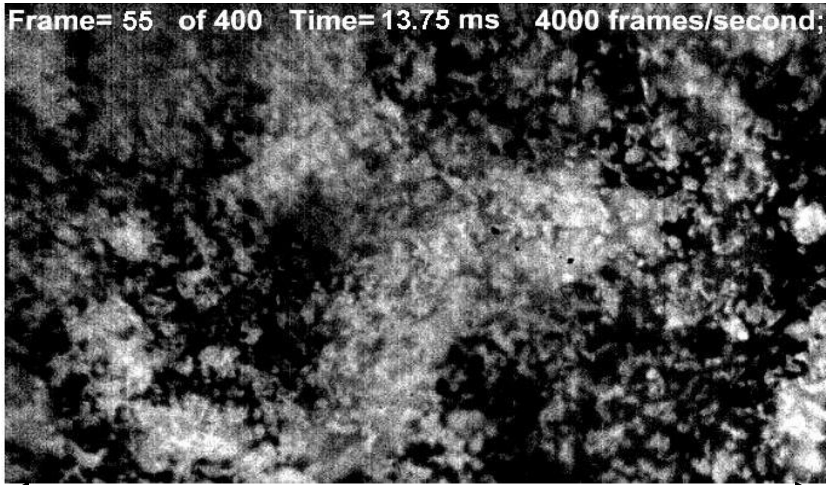
- **We have made the first direct observations of clustering <u>inside</u> a fluidized bed of cohesive particles in PSRI's Entrainment Research Unit**

Particle Clustering Phenomena in/above Fluidized Beds and in CFB Risers

	Clusters in Fluidized Beds	Clusters in CFB Risers
Cluster size	5 to 100 particles:	10 particles to millions of particles
	10^{-5} to 10^{-3} meters	10^{-3} to 1 10^{-3} meters
Superficial gas velocity	< 1 m/s	~ 10 m/s
Other	Tightly bound clusters do not deform	Malleable clusters that can deform with high shear rates

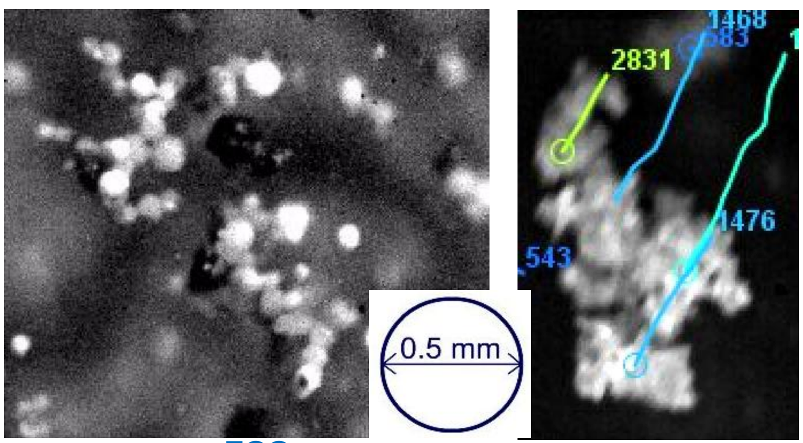
Clustering in/above Fluidized Beds

Clusters of 70 μm polyethylene clusters inside a fluidized bed



3 mm

Clusters of 70 μm FCC and polyethylene 5 m above a fluidized bed



FCC **Polyethylene**

Ex1: high speed PIV of clusters

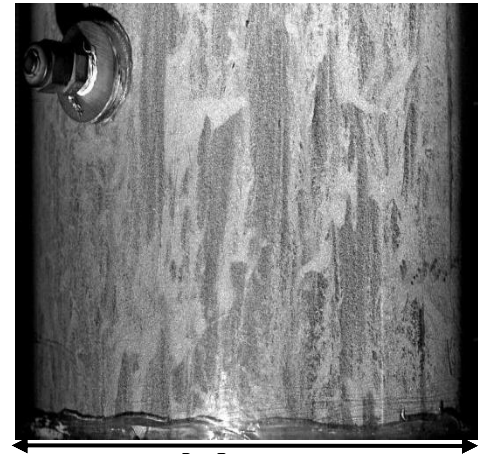
Ex2: FCC in FB Ex3.FCC above FB

Clustering in Risers

Clusters of 750 μm HDPE in NETL 12” riser

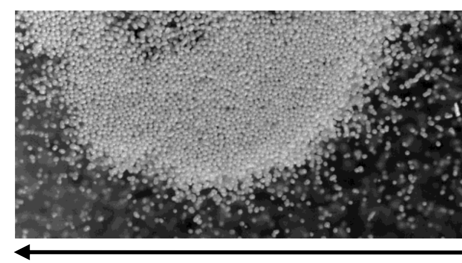
1 m

Clusters of 70 mm FCC in PSRI CFB riser



0.2 m

Cluster of 750 μm HDPE in NETL 12” riser



0.2 m

Ex1: NETL Riser 750 mic HDPE

Ex2: PSRI Riser 70 mic FCC

Future Applications: High Speed PIV Validation of DEM Simulations

- DEM CFD is a growing and promising field
- High speed PIV measures the same data that is generated by a DEM simulation
- A project was started in 2010 to apply high speed PIV to a small, well controlled fluidized bed for validation of DEM simulations
- To keep the number of particles small enough that DEM simulations can run in reasonable times, fluid bed dimensions are kept small (3” x 9” cross section) and particle size large (6mm).
- Total number of particles in the range of 25,000 to 100,000

Preliminary Examples of hsPIV Measurements in a Small Fluidized Bed

- Preliminary experiments were done in a quickly constructed fluid to show the kind of data produced by high speed PIV
- Examples
  - Fluid Bed startup
    - Particles only
    - Particles tracked and pseudocolored with velocity magnitude
    - Particles only and pseudocolored velocity side-by-side
      with white background, looks identical to DEM simulation
  - Mixing of stratified layers of different density
    - Particles only
    - Velocity pseudocolored
    - Example trajectories showing mixing

High Speed Particle Imaging of Particle Flow Fields
Results and Conclusions

- High quality visualization of dense particle flows has been achieved, including inside dense flow fields
- Accurate measurement of the fluctuating component of particle velocity. Data sample rates for particle velocity are high enough (0.1 to 1.0 GHz) to accurately calculate parameters like Granular Temperature
- Measurement of particle-wall slip boundary condition in CFB risers
- A high speed jet flow phenomenon has been identified in CFB
- Particle rotation plays an important role and may act as an energy sink
- The size and velocity distributions of particle clusters have been measured in-situ in and above a fluidized bed of cohesive particles. Particle clusters in fluid beds are distinctly different than clusters in CFB risers.
- Achieved full field mapping of all (>95%) of visible particles in a small fluid bed. Experimental results are indistinguishable from a DEM simulation.

hsPIV Measurements for DEM Validation: Future Plans

- We have a source of inexpensive particles with tight tolerances on sphericity and diameter.
- The particles also are available in different densities and colors.
- This offers the opportunity to study many different processes, including particle mixing, jet injection, and almost any flow geometries
- To study a unique flow geometries, all we need is a small transparent model
- The number of particles can be increased as computational speed improves
- Particle size can be decreased down to around 1mm with high speed PIV mapping of entire fluid bed

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High Speed Imaging of Particle Motion and Rotation

The rotational speed of one thousand particles was measured.
Approximately 20% of particles were rotating.