High Speed Particle Imaging:
Visualization and Measurement of High Concentration Particle Flow Fields

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High Speed Particle Imaging ?

- **The use of high resolution, high speed optical imaging -- with and without a borescope -- to visualize *and* measure particle motion *at all locations* in particle flow fields of high particle concentrations.**

- **Using "fastest" high resolution, high speed camera available: Vision Research v12, with 1280 x 800 pixel resolution (12 bit grey scale) at 6200 frame per second. Up to 1 million frames per second at low resolution.**

- **Borescope diameter down to 6 mm to reduce interference with particle flow field.**

High Speed Particle Imaging: *Quantitative*

Measured parameters:

- **2D particle trajectory and velocity**
- **Particle concentration**
- **Particle collisions and rotation**
- **Particle size and shape**

- **Accuracy is high enough (uncertainty ~ ±1% for particle velocity) and sampling rate fast enough to resolve the 2D fluctuating components of particle velocity.**

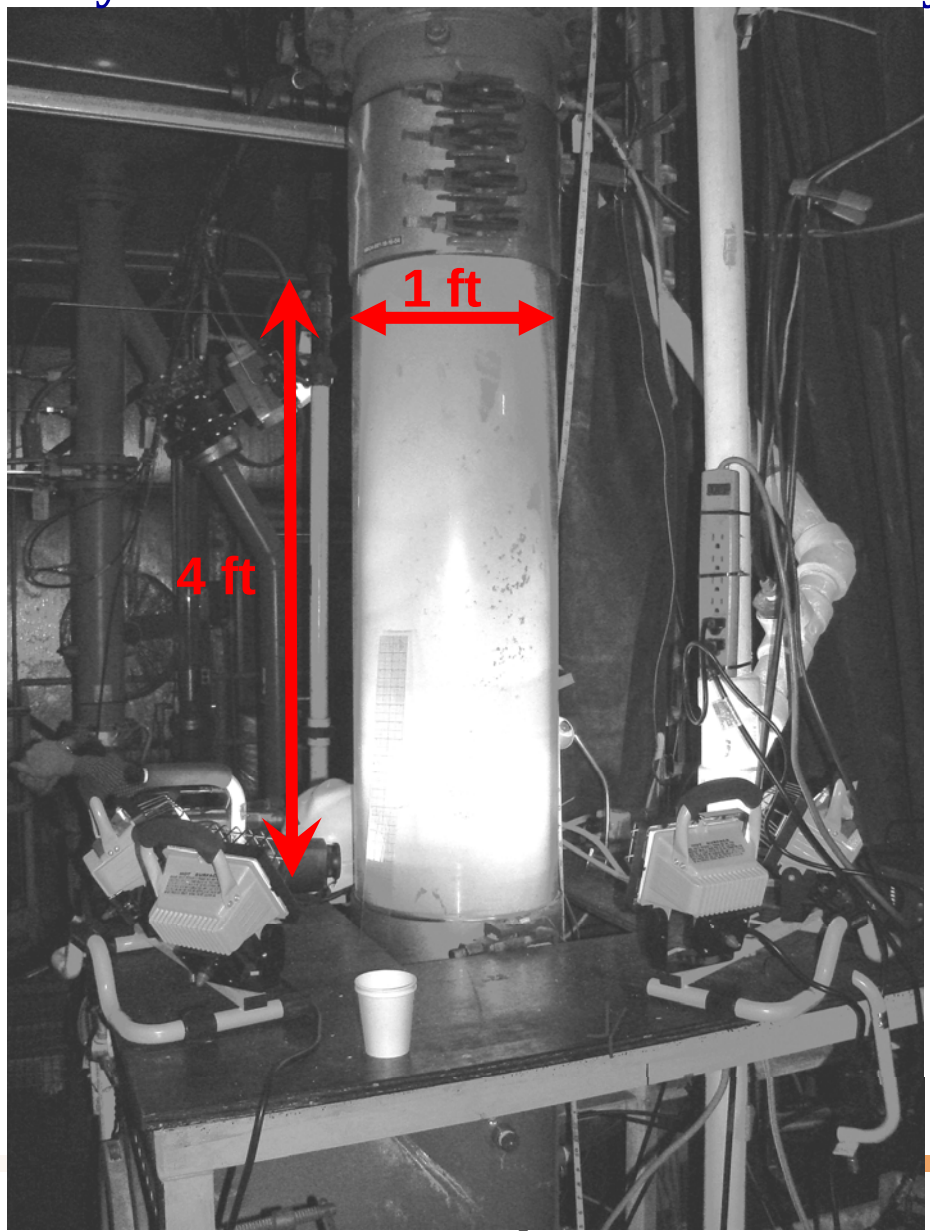
High Speed Particle Imaging: *Qualitative*

Generates high resolution, high speed videos of particle flow phenomena.

Measurements are made from the high speed videos.

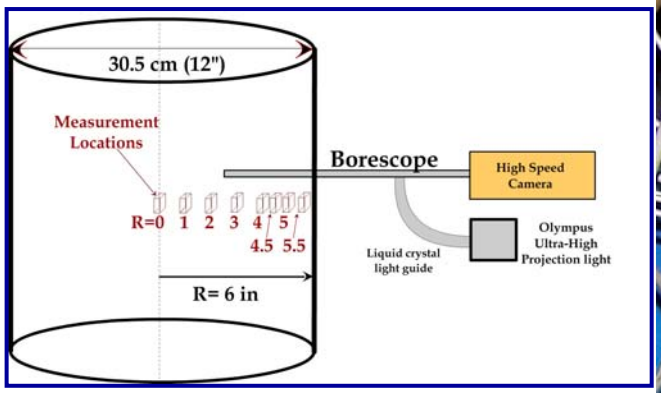
This is the only measurement technique for which data can be interpreted by viewing a high speed video of the particle flow field from which the data were derived.

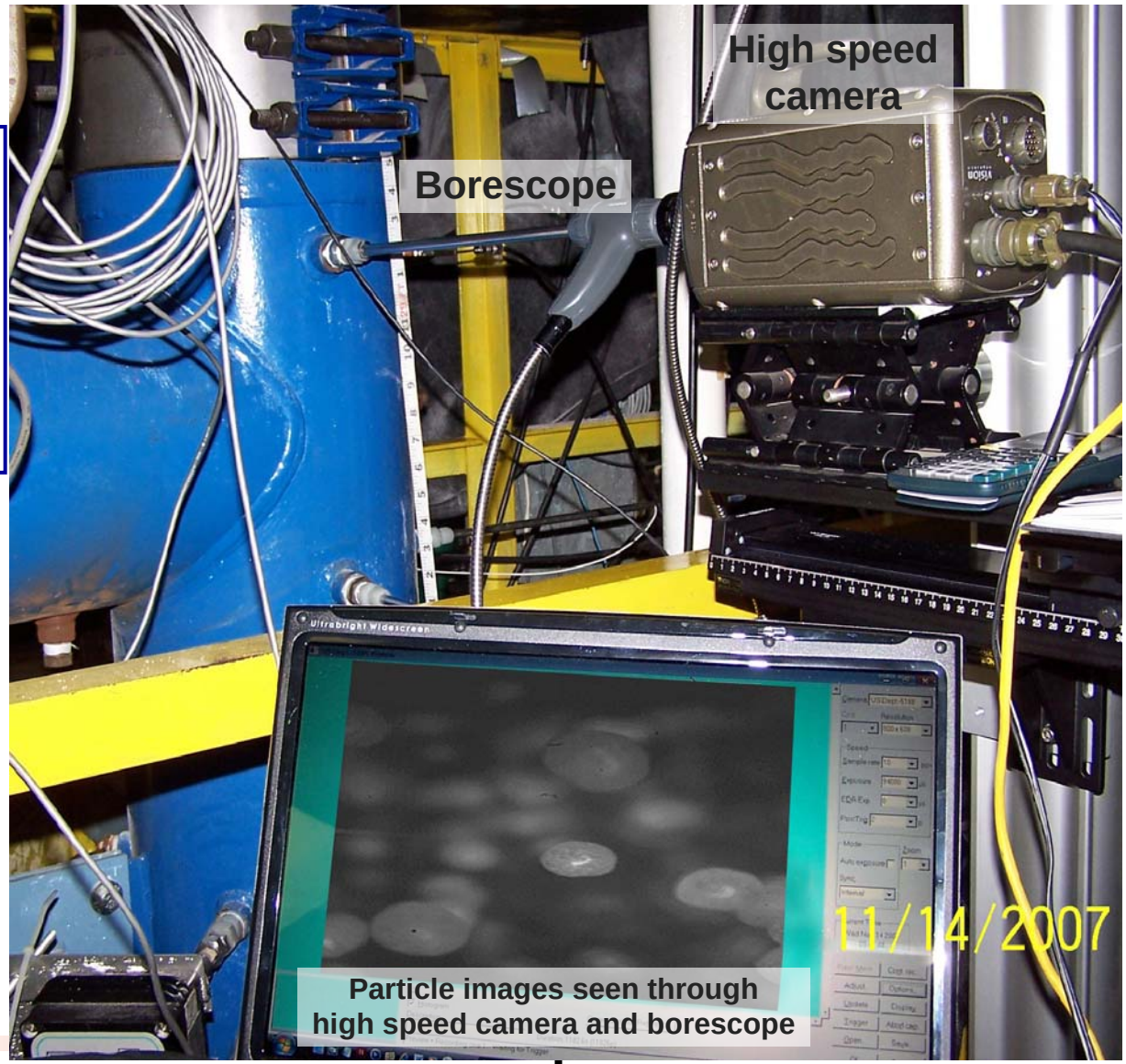
Examples from the NETL Cold Flow Circulating Fluidized Bed facility. A 4’ x 1’ section of the riser at y=30’.



Measurement Locations & Conditions in NETL's Cold Flow Circulating Fluidized Bed Riser

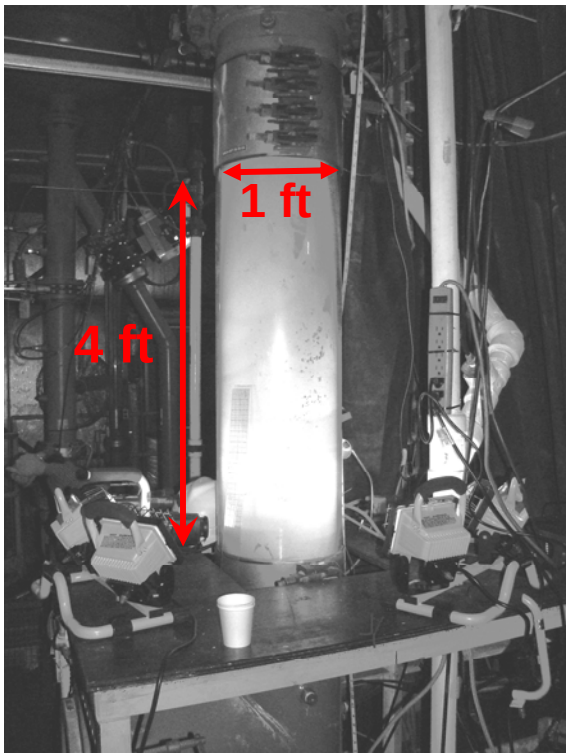
Measurements are made through a borescope along a radial scan shown below.





Particle images seen through high speed camera and borescope

Examples from a Transparent Section of NETL CFCFB Riser



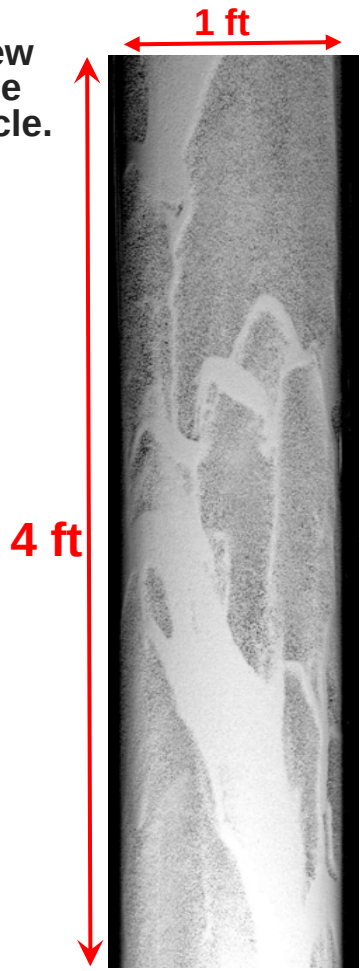
High speed videos were shown of the following phenomena:

- Varied field-of-view from 4ft to single particle
- Cluster phenomena: packed leading edge of stable clusters
- 2D Velocity and concentration mapping of large clusters
- Measurement of random particle motion (temperature)
- Example of particle tracking at near maximum concentration: Couette shearing example
- High speed motion of particle collisions and rotation inside riser
- Clustering measurements in PSRI labs in Chicago

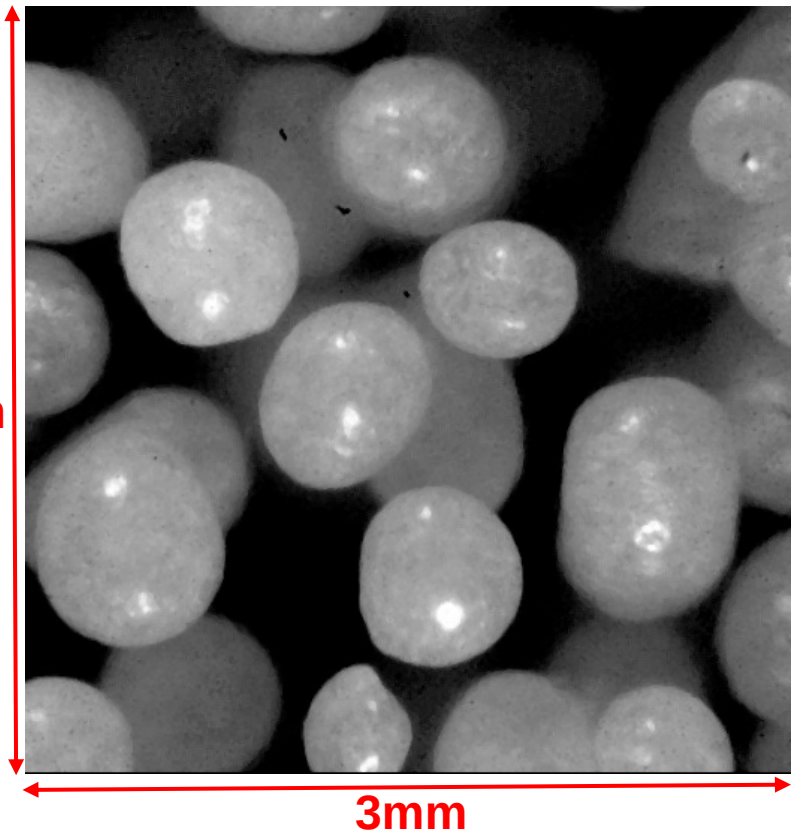
Range of field-of-view size: from entire flow field down to resolution of single particle motion:

(High speed videos of the full range of field-of-view sizes were shown in the conference. For copies of high speed videos, contact Franklin.Shaffer@netl.doe.gov)

Field-of-view shows large scale particle. clusters



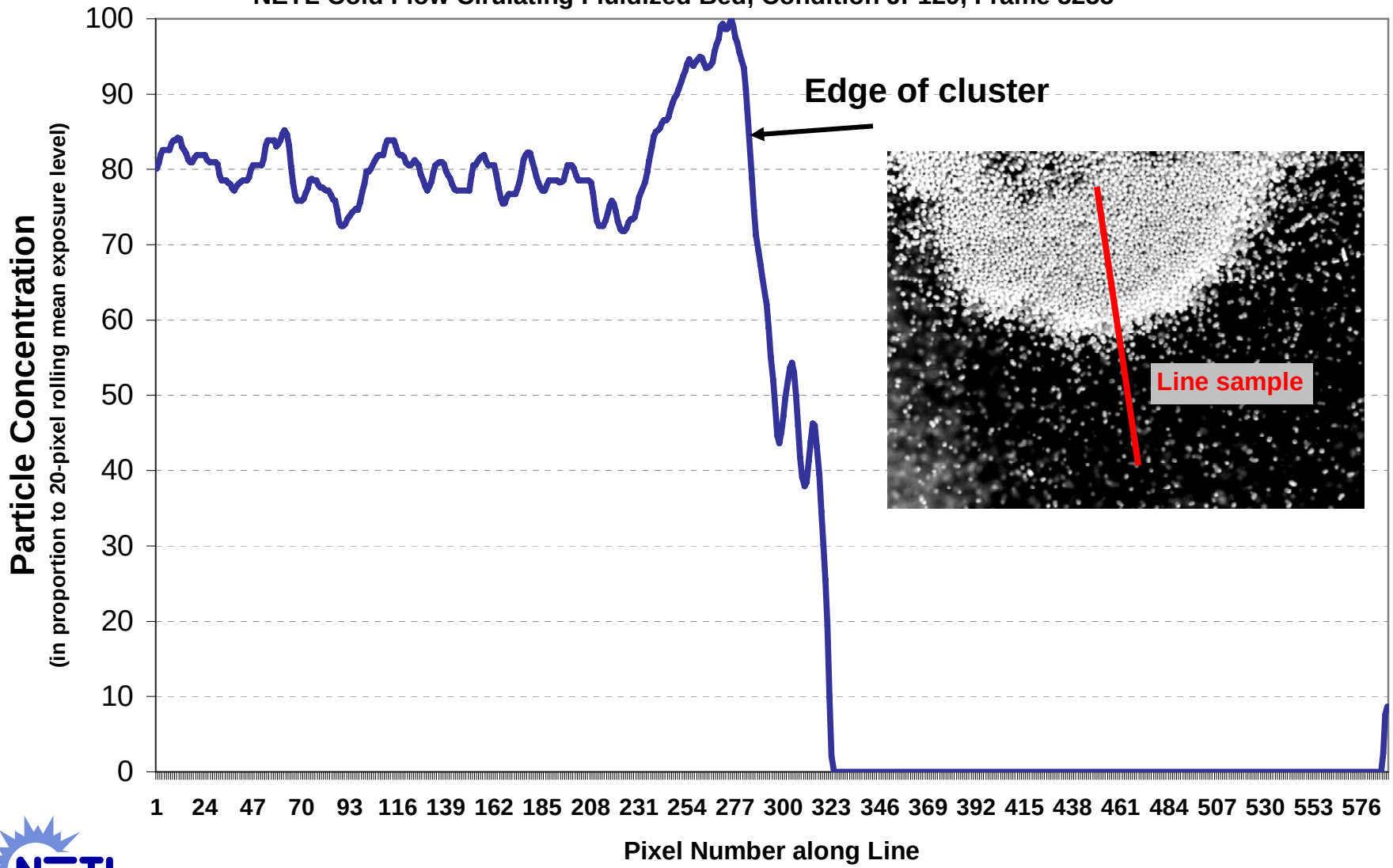
Field-of-view is magnified to study behavior of individual particles.



Example of packed leading edge of a stable cluster.

Particle Concentration along Line Sample through Cluster Edge

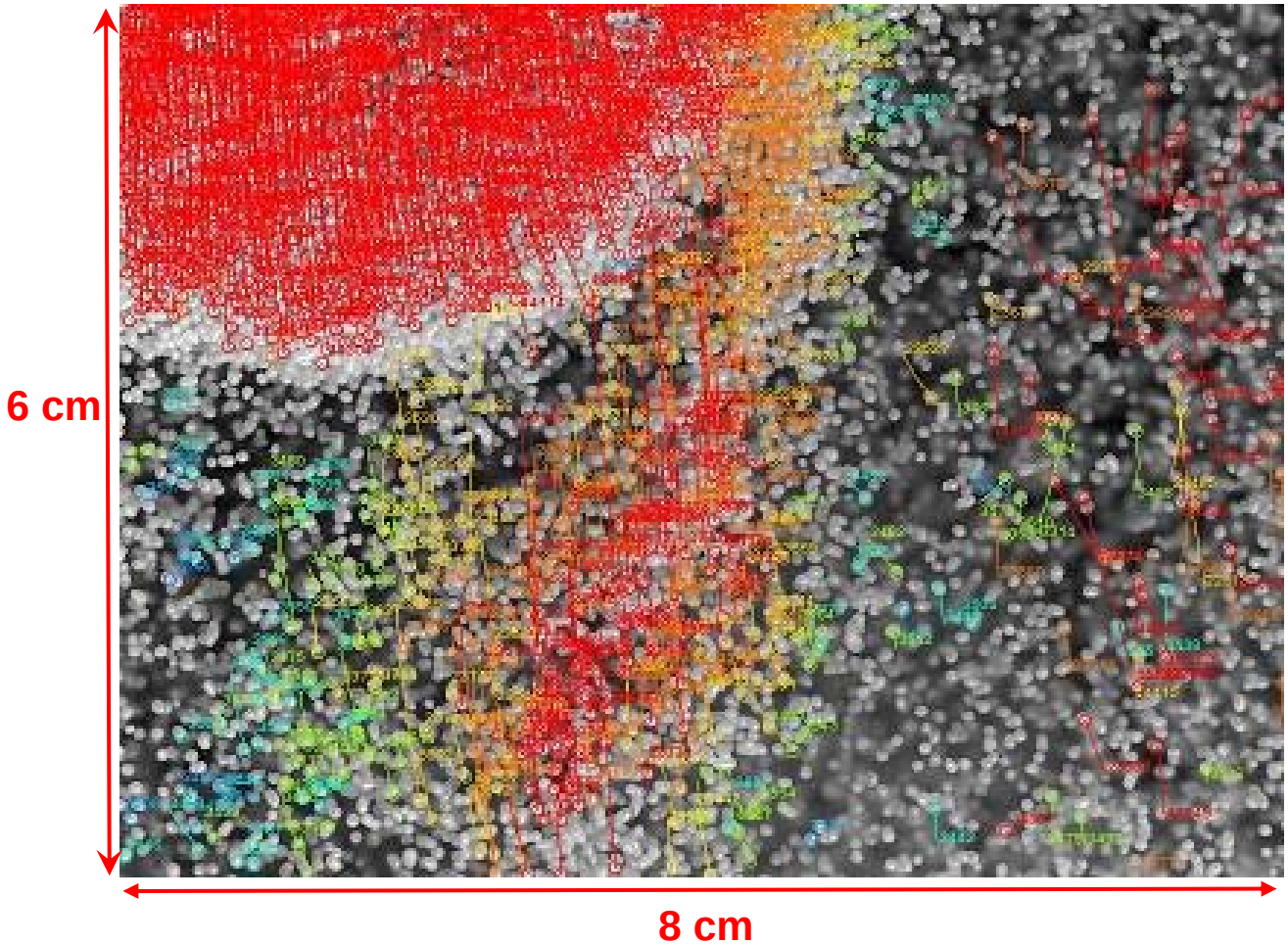
NETL Cold Flow Cirulating Fluidized Bed, Condition JP129, Frame 5255



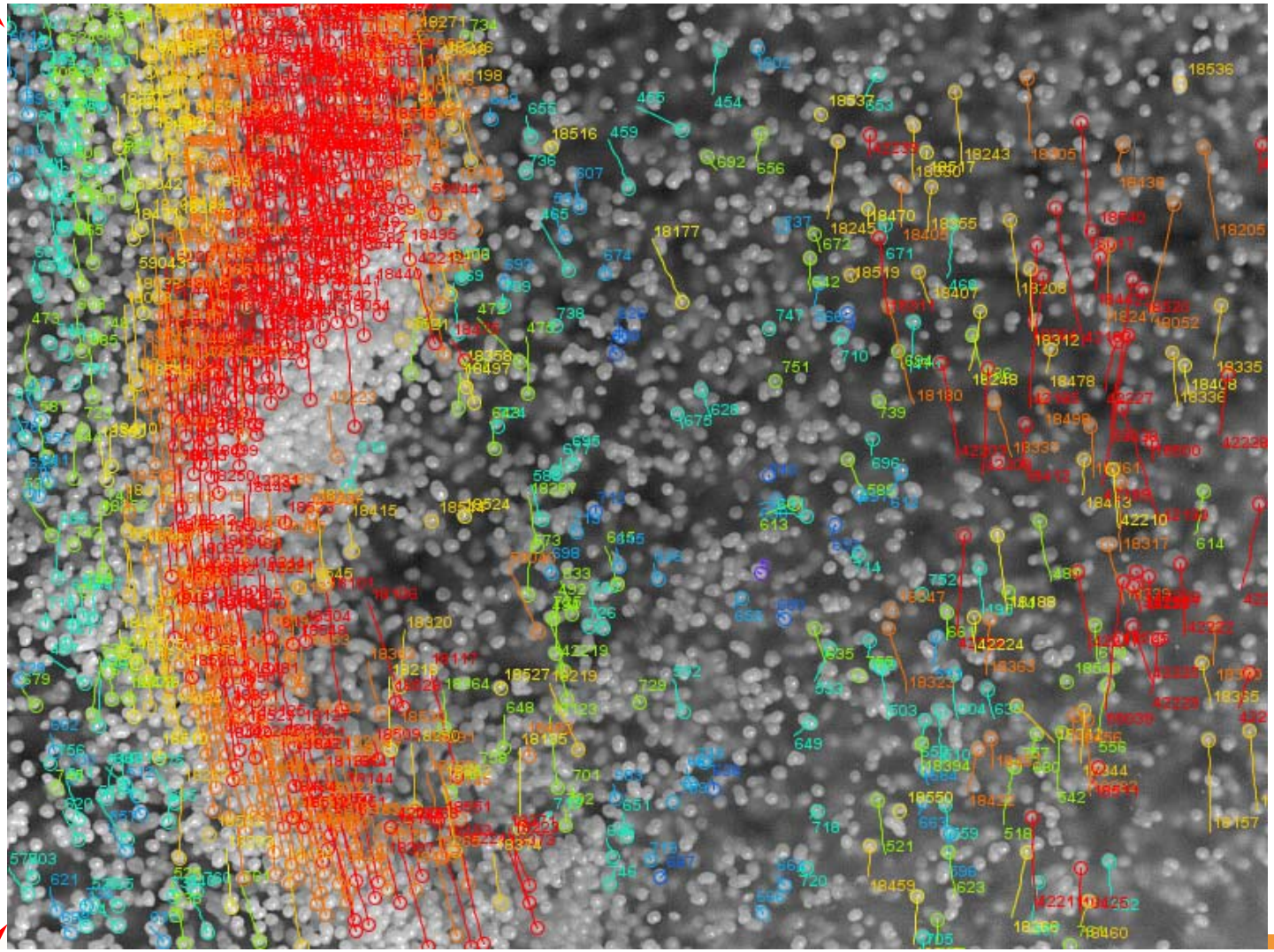
Software has been developed by the NETL to automatically recognize and track particles in dense particle flow fields.

Example 1: 2D particle tracking and concentration mapping of a large cluster.

(A high speed video of this was shown in the conference.)

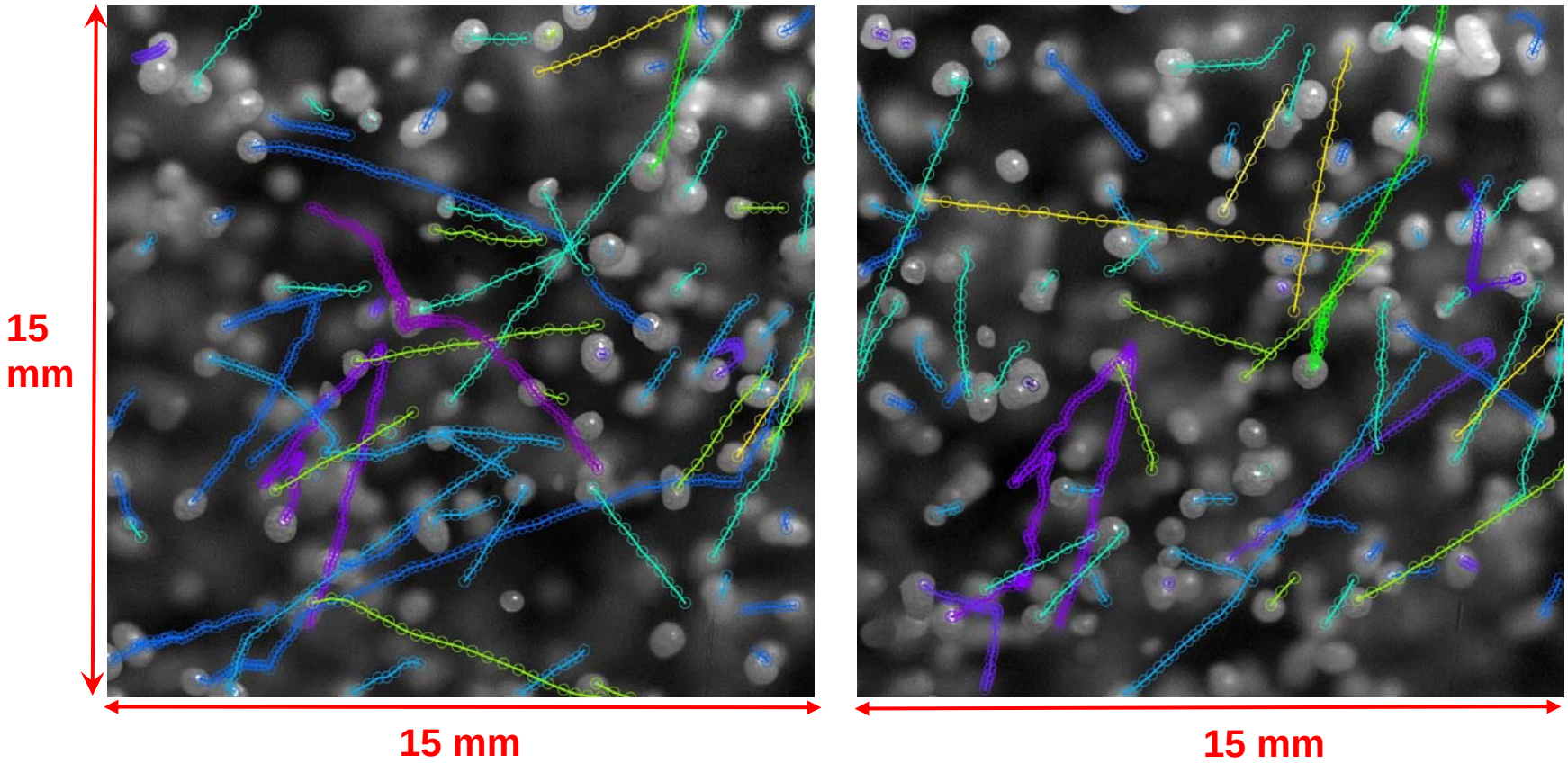


Example 2: 2D velocity and concentration map of large "streamer" clusters.
Each particle trajectory is identified with unique number, allowing data to be interpreted by studying flow field phenomena, such as clustering, collisions, rotation, etc.
(A high speed video was shown in the conference.)

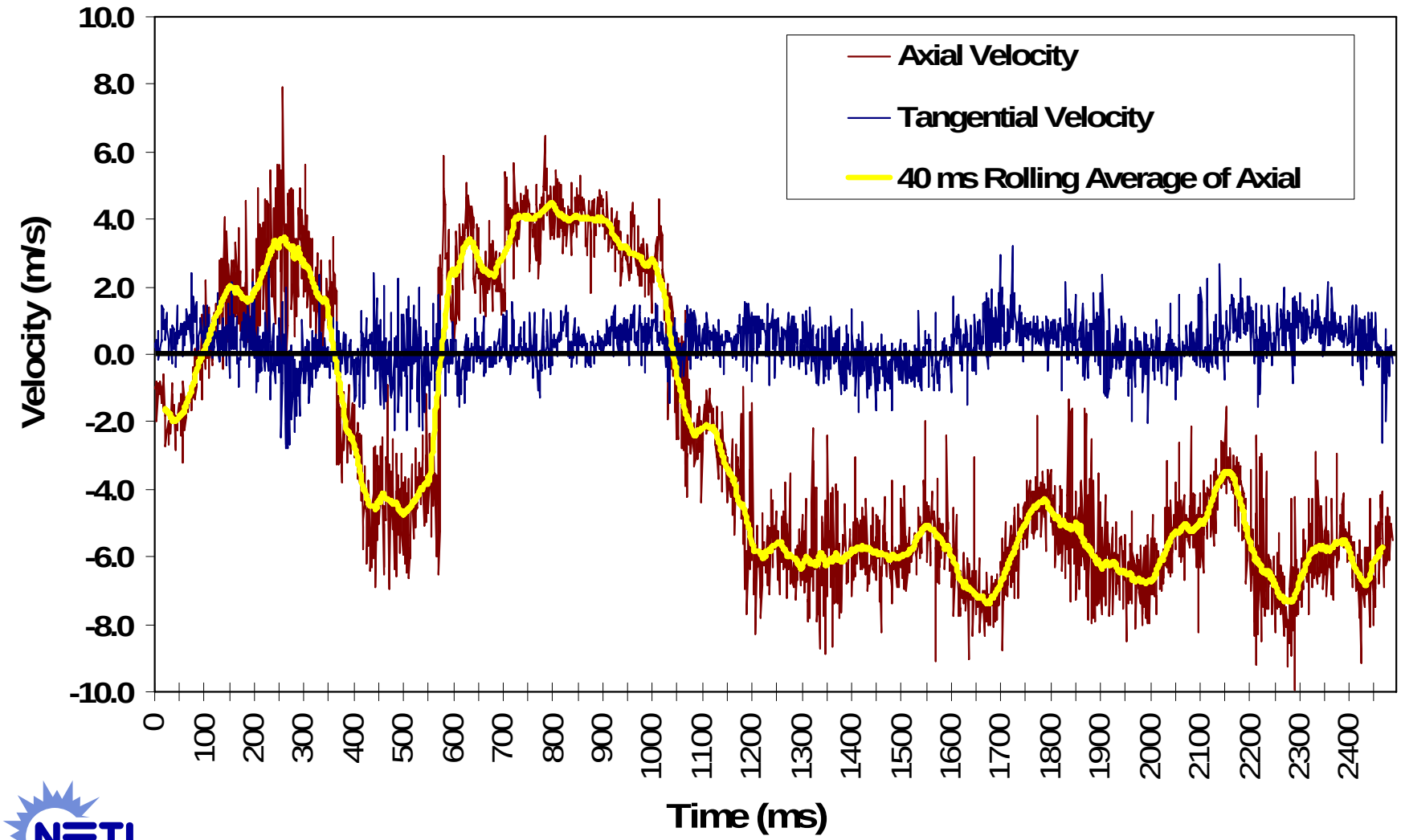


Software has been developed by the NETL to automatically recognize and track particles in dense particle flow fields, even for particles in completely random motion. This is perhaps the first direct measurement of particle "temperature" phenomenon.

(High speed videos of this were shown in the conference.)

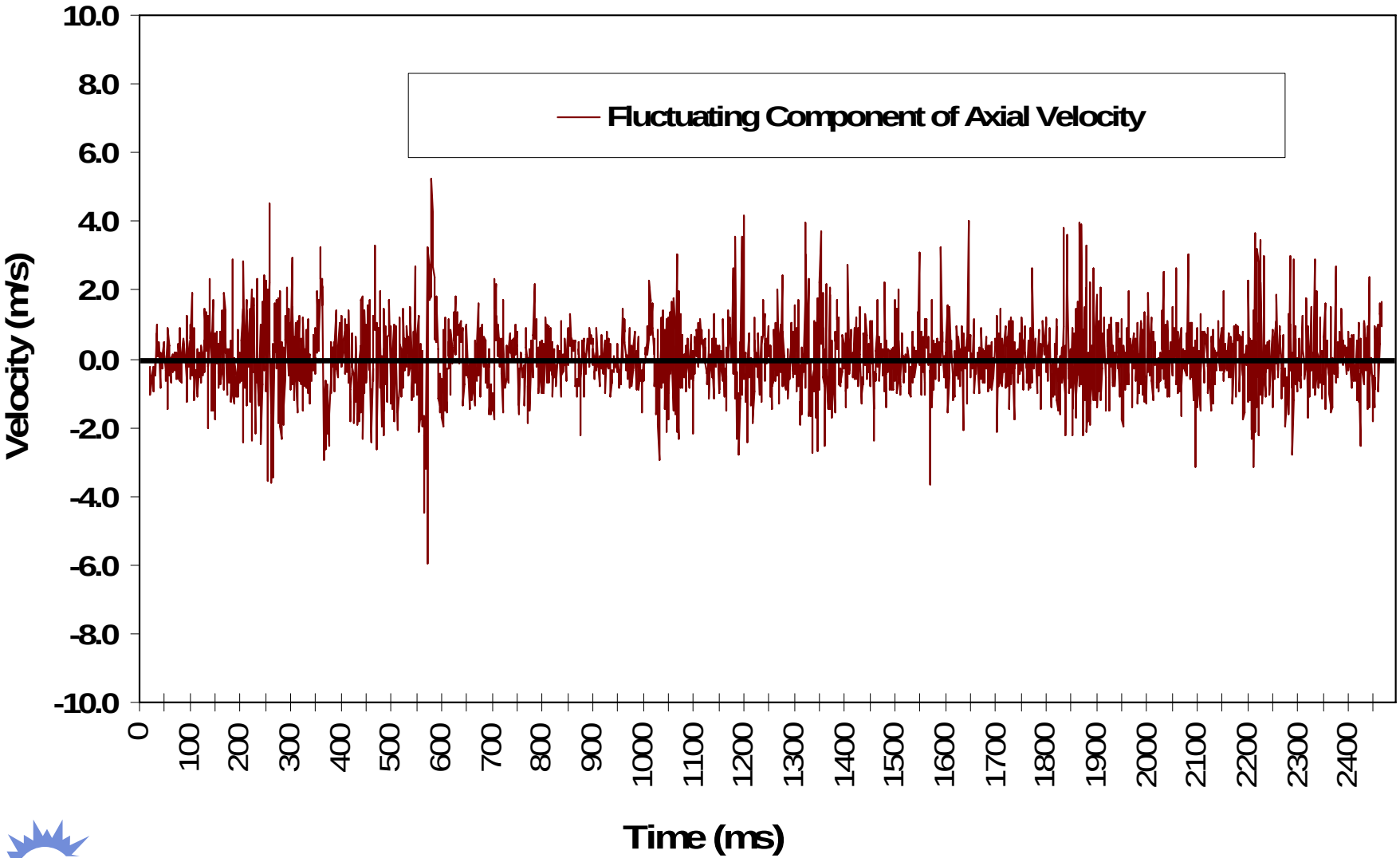


Particle Velocity Data for HDPE particles 0.5” from Riser Wall, condition JP123.
Two components (directions) of particle velocity are measured.
The yellow line indicates large fluctuations in flow direction caused in part by large clusters.



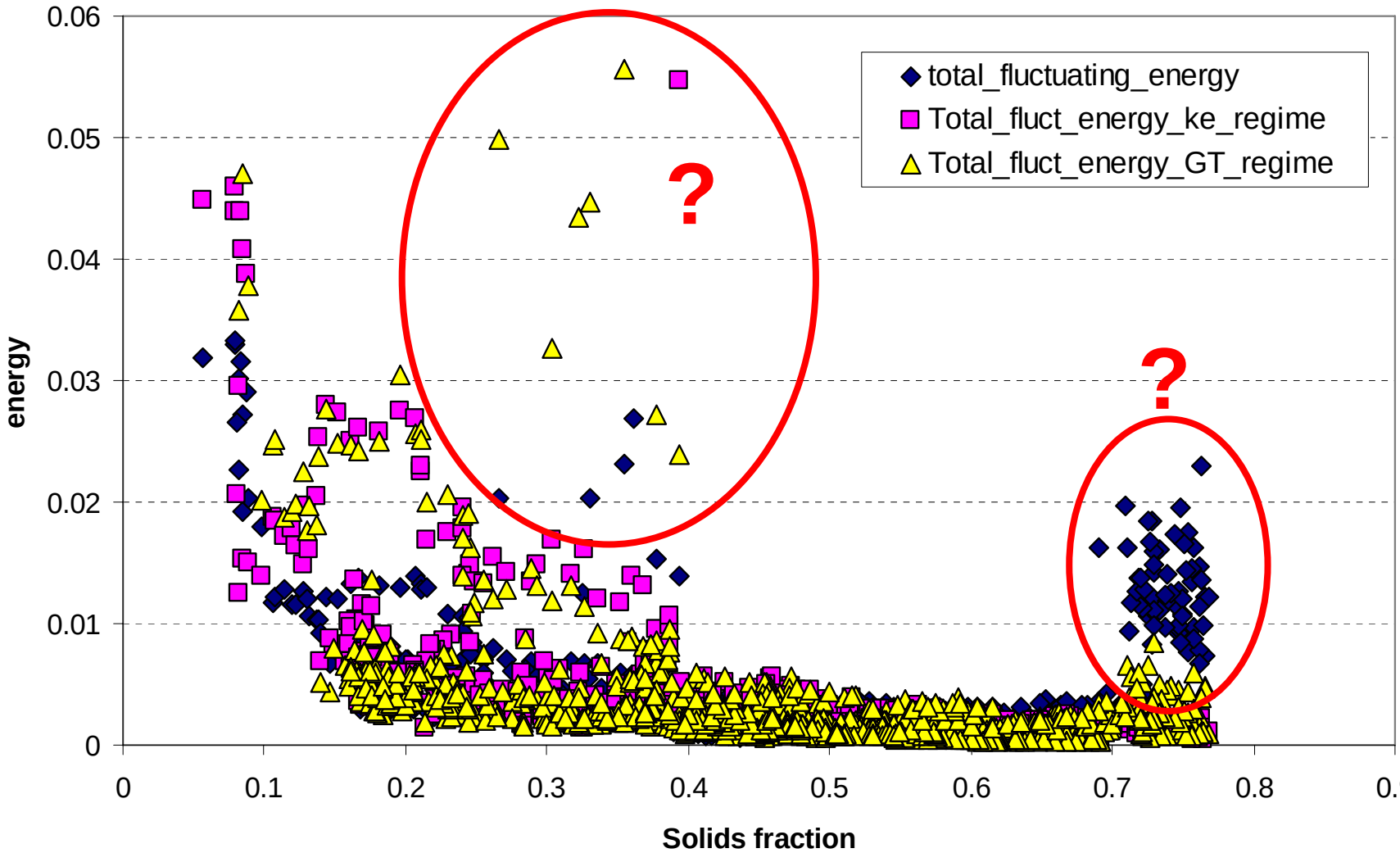
Fluctuating Component of Particle Velocity, 0.5” from Wall, JP123

The large amplitude, low frequency component of velocity caused by clusters is removed, since, by definition, particle fluctuations approach zero inside clusters.



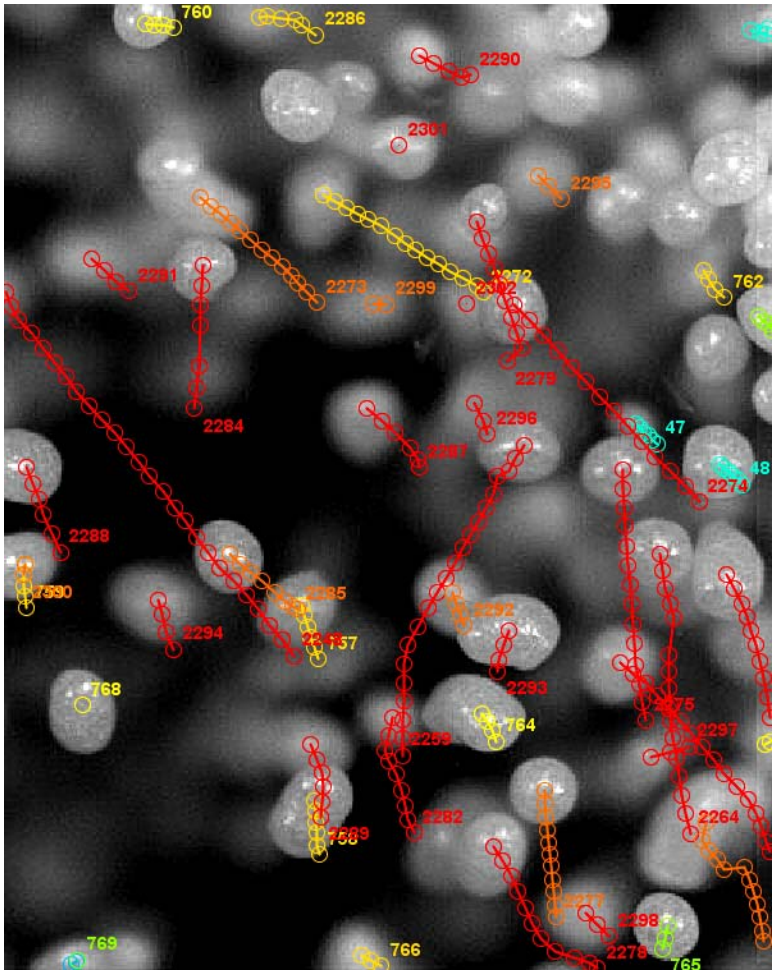
Example of Data Interpretation with High Speed Video: Fluctuating Particle Energy.

The anomalies in the data (shown inside red circles) could be understood only by reviewing high speed videos of the particle motion. The anomalies were caused by the field-of-view overlapping the edge of a cluster. Without the ability to visually review the actual particle motion, these out-of-trend data might not be understood.

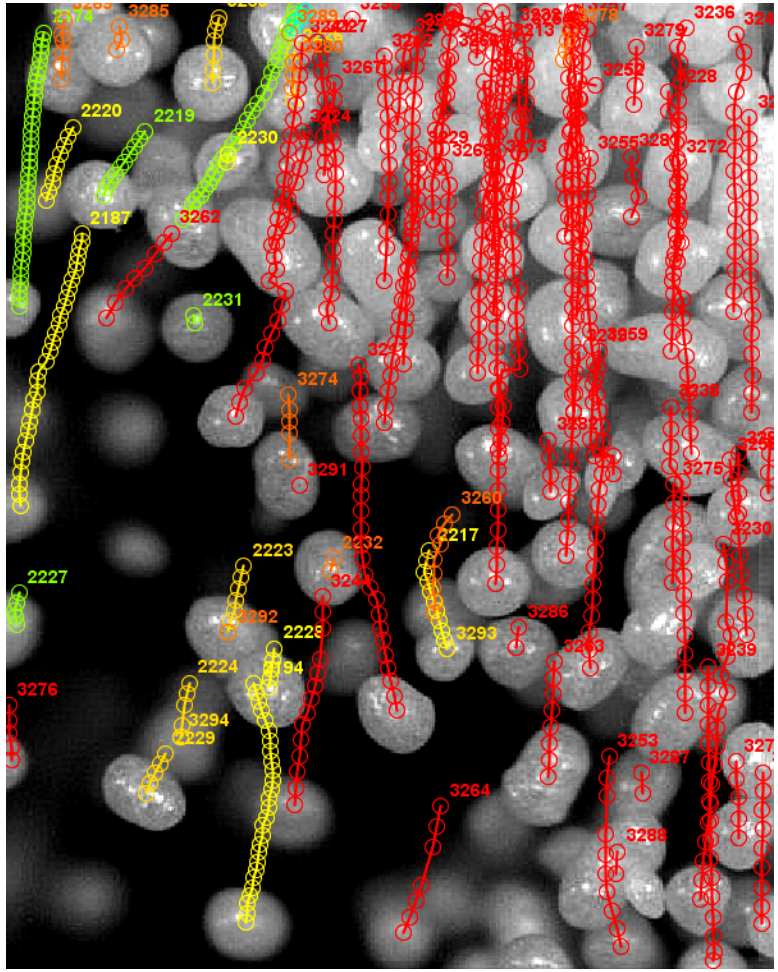


Anomalies in data were caused by measurements at the edge of a cluster where concentration was high but fluctuating energy was also high because particles were colliding with the edge of the cluster.

(High speed videos were shown at the conference)



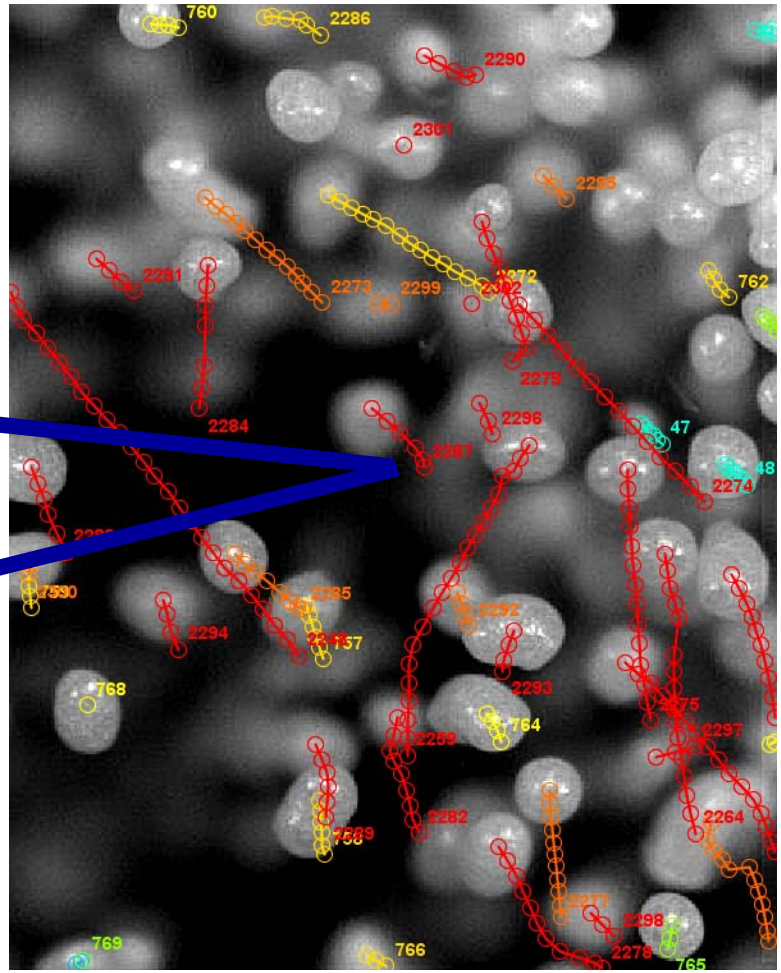
Low concentration:
high fluctuating energy



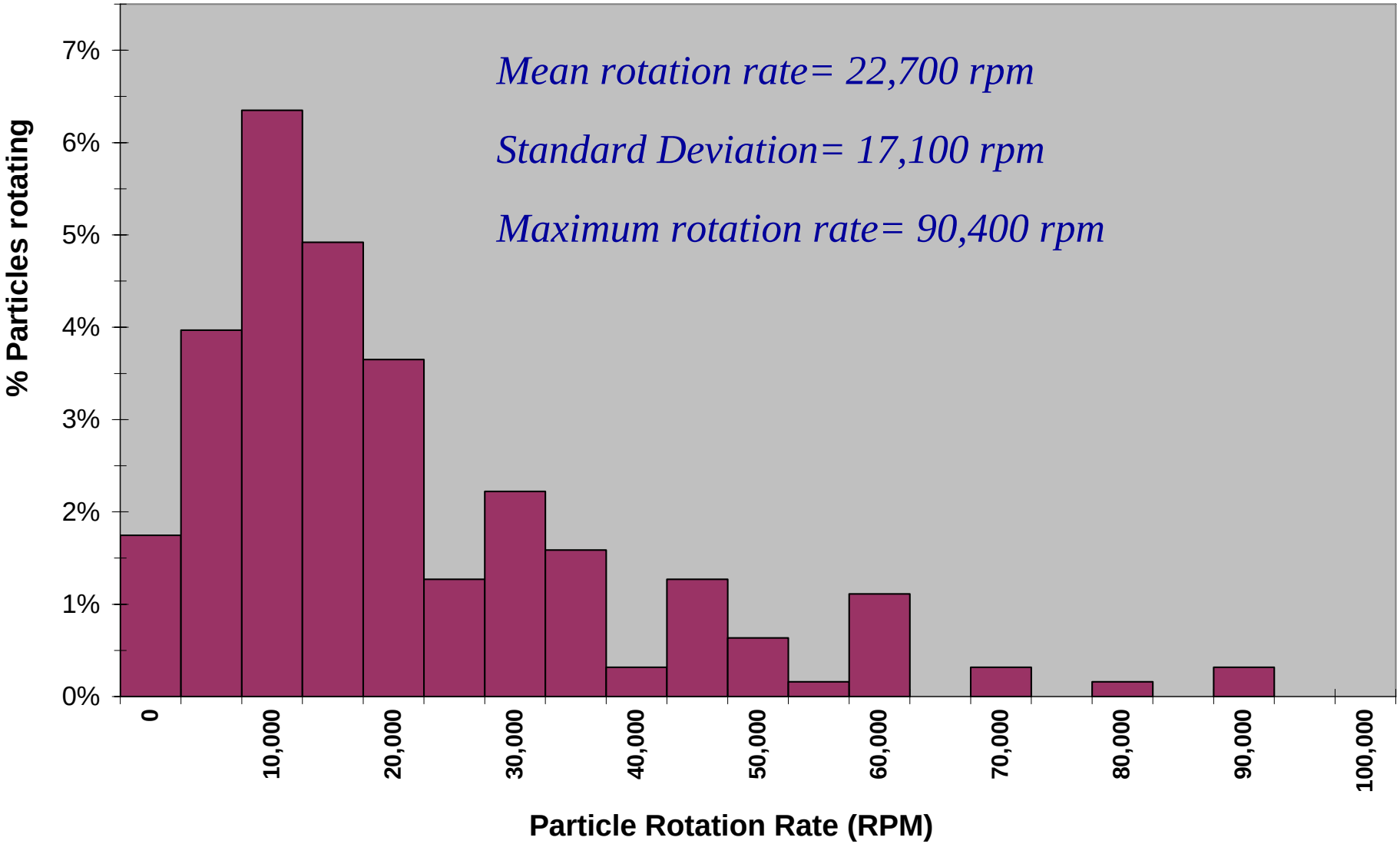
Edge of a cluster: high concentration
and high fluctuating energy

Future Plan: LDV measurement of gas velocity inside particle flow field measured with high speed particle imaging. This will provide the first accurate measurement of gas drag inside dense particle flows.

LDV



High speed imaging has shown that about 20% of particles are rotating at high speeds in the riser flow field. Rotation appears to be caused by particle-particle collisions. Conversion of translation kinetic energy to rotational kinetic energy seems to be an important mechanism of energy dissipation/loss by the particle phase. The rotation speed of 1000 particles was measured and is plotted below.



Summary

- **A high speed particle imaging system has been developed and is being applied at the NETL and PSRI**
- **Image analysis software to automatically recognize and track particles through thousands of high speed video frames at high particle concentrations has been developed by the NETL. A patent application is in process.**
- **Future plans include simultaneous measurement of gas velocity with LDV and particle velocity/concentration with high speed particle imaging.**
- **High speed particle imaging is unique in the ability to interpret measurement data by reviewing high speed videos of the particle motion from which the data were derived.**
- **High speed particle imaging can accurately measure two directions of the mean and fluctuating components of particle velocity.**
- **Questions remain regarding analysis of high speed PIV data**
  - How to define region over which to calculate meaningful mean and fluctuating components of particle velocity with presence of clusters

Thank You!

For copies of the high speed videos shown in the conference, contact Frank Shaffer at Franklin.Shaffer@netl.doe.gov , 412-386-5964

Please specify which high speed video you would like.

Some high speed videos shown in the conference presentation are large (several GBytes) so they may need to be sent through regular mail on DVD's.