A New View of Riser Flow Fields using High Speed Particle Imaging

Frank Shaffer, Balaji Gopalan, Ron Breault
NETL

Ray Cocco, Roy Hays, Reddy Karri, Ted Knowlton
PSRI

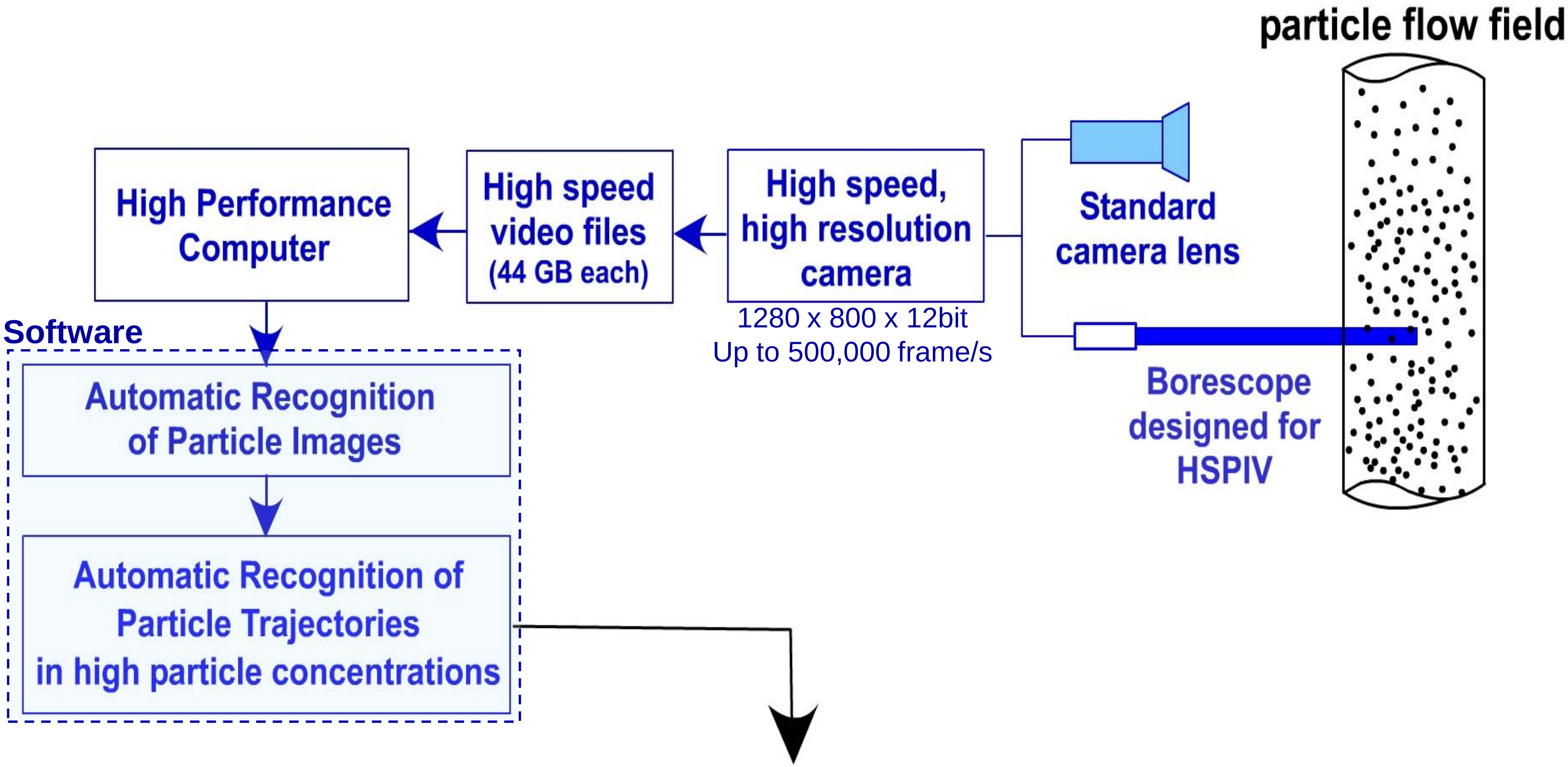
NETL Multiphase Flow Workshop
May 4-6, 2010

NETL has developed a new High Speed Particle Imaging System for observation/measurement of high concentration particle flows

The NETL high speed particle image velocimetry (HSPIV) system is intended to make major advances in quality of experimental data for high concentration particle flows, so data can be compared directly with modeling parameters.

This presentation will
(1) explain the NETL HSPIV system and
(2) present new results for fluidized beds and risers

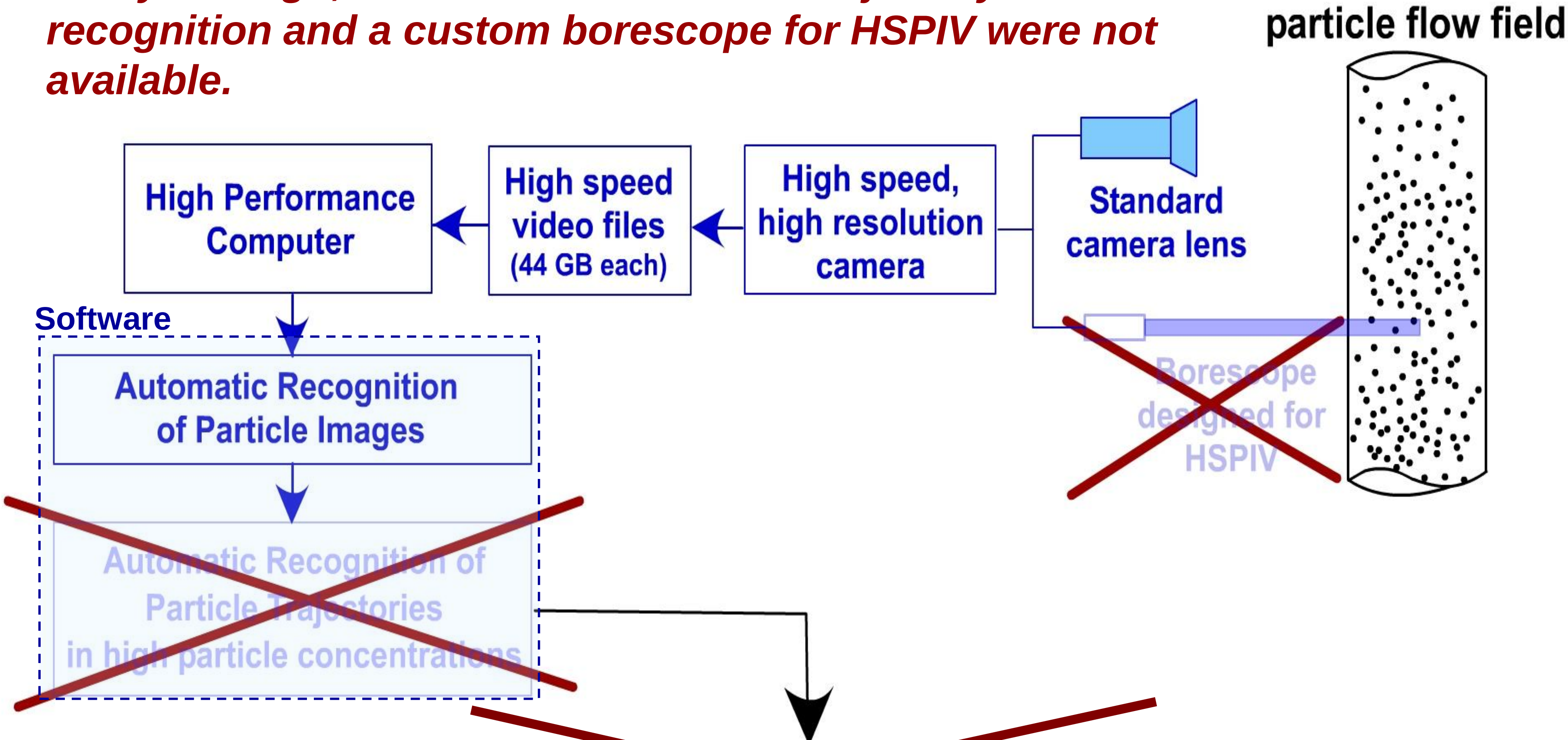
Basic Steps of HSPIV



Data describing particle flow fields.
Goal is to produce the same data produced by CFD models.

Basic Steps of HSPIV: *Missing Steps*

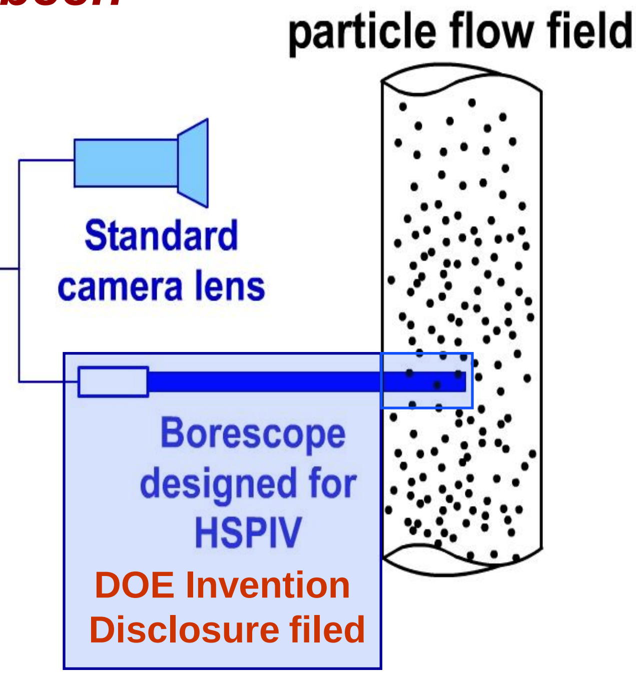
Two years ago, software for automatic trajectory recognition and a custom borescope for HSPIV were not available.



~~**Data describing particle flow fields.**~~
~~**Goal is to produce the same data produced by CFD models.**~~

Basic Steps of HSPIV: *Automatic Trajectory Recognition*

Much of the effort in this project to date has been in developing software tools for automatic trajectory recognition



High speed, high resolution camera → High speed video files (44 GB each) → High Performance Computer → Automatic Recognition of Particle Images → Automatic Recognition of Particle Trajectories in high particle concentrations

Patent pending.
US Patent App. 12765317

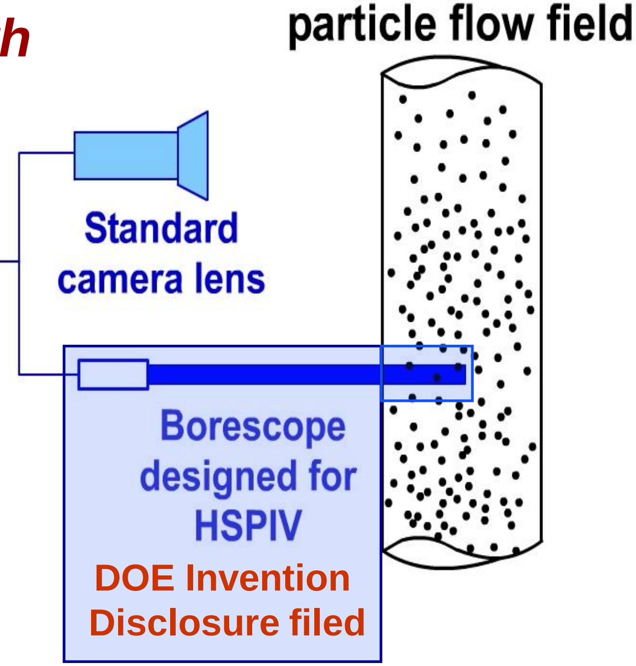
Automatic Particle Trajectory Recognition:

- **Very difficult at high particle concentrations**
- **Starts with a 44 GByte file with 40 million particle images**
- **Trajectories overlap, particle images overlap, and particle images are often missing**
- **Software has been developed and is in patent pending status (US Patent App. 12765317).**
- **Software can recognize trajectories even in random motion and at maximum particle concentration**

Basic Steps of HSPIV: *Custom Borescope*

A custom borescope with optical parameters optimized for HSPIV has been developed with Gradient Lens Corp.

High Performance Computer ← High speed video files (44 GB each) ← High speed, high resolution camera



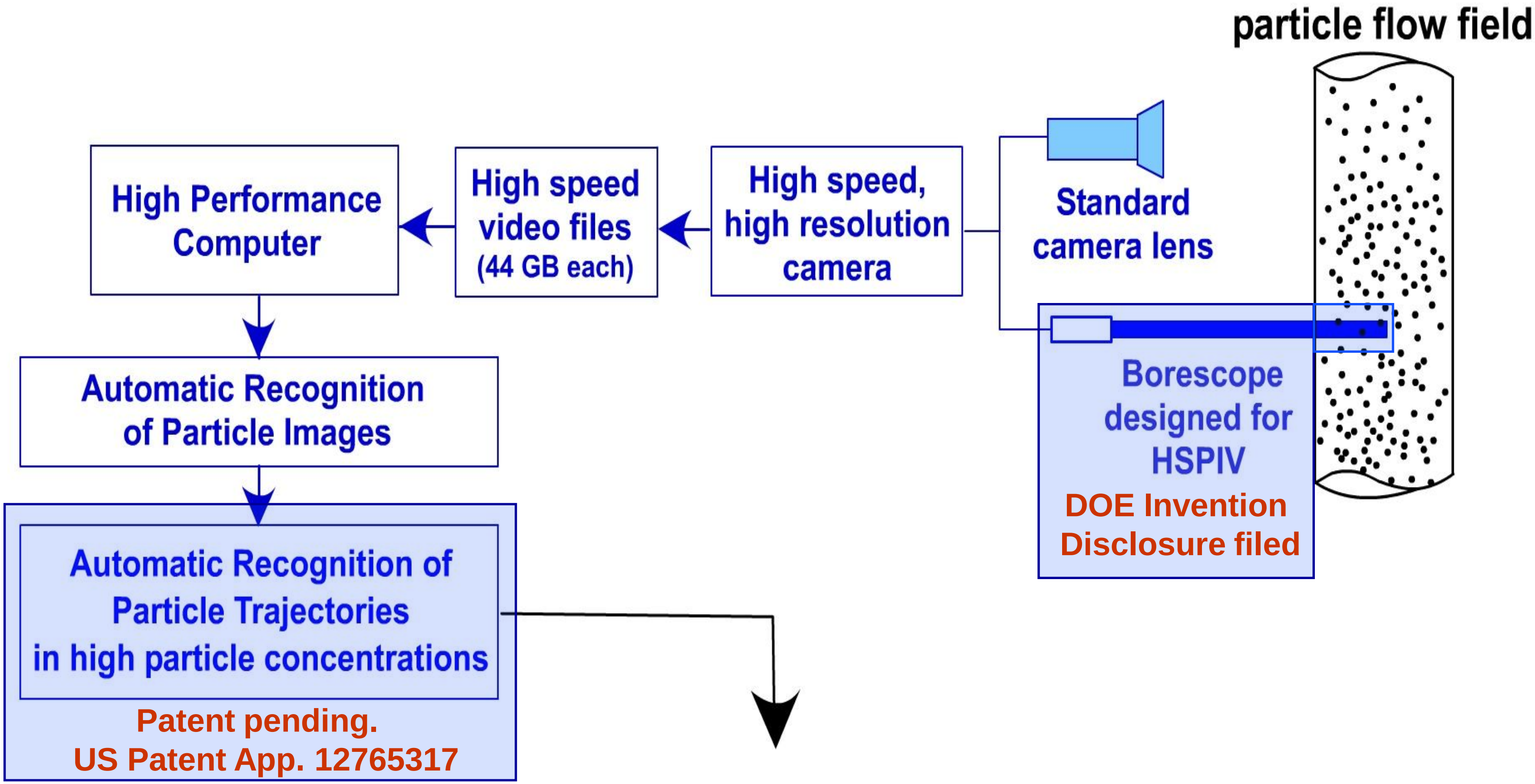
High Performance Computer → Automatic Recognition of Particle Images → Automatic Recognition of Particle Trajectories in high particle concentrations

Patent pending.
US Patent App. 12765317

<u>Development of custom borescope for HSPIV:</u>

- **Standard borescopes designed with infinite depth-of-field**
- **HSPIV needs thin depth-of-field**
- **Standard borescopes focus far from borescope tip**
- **HSPIV needs to focus and illuminate close to borescope tip**
- **Custom borescope designed with Gradient Lens Corp**
- **borescope is in use and producing much better results**
- **DOE Invention Disclosure filed.**

Basic Steps of HSPIV: *All Steps Completed*



Data describing particle flow fields.
Same data produced by CFD models.

Data Produced by HSPIV:

Three types of data produced by HSPIV:

1. **Simultaneous "point" measurement of individual particle motion and concentration**
2. **Large area maps of velocity and concentration**
3. **High speed videos of particle flow fields with recognized trajectories shown and identified with ID number. Allows data to be studied by viewing particle motion that produced the data.**

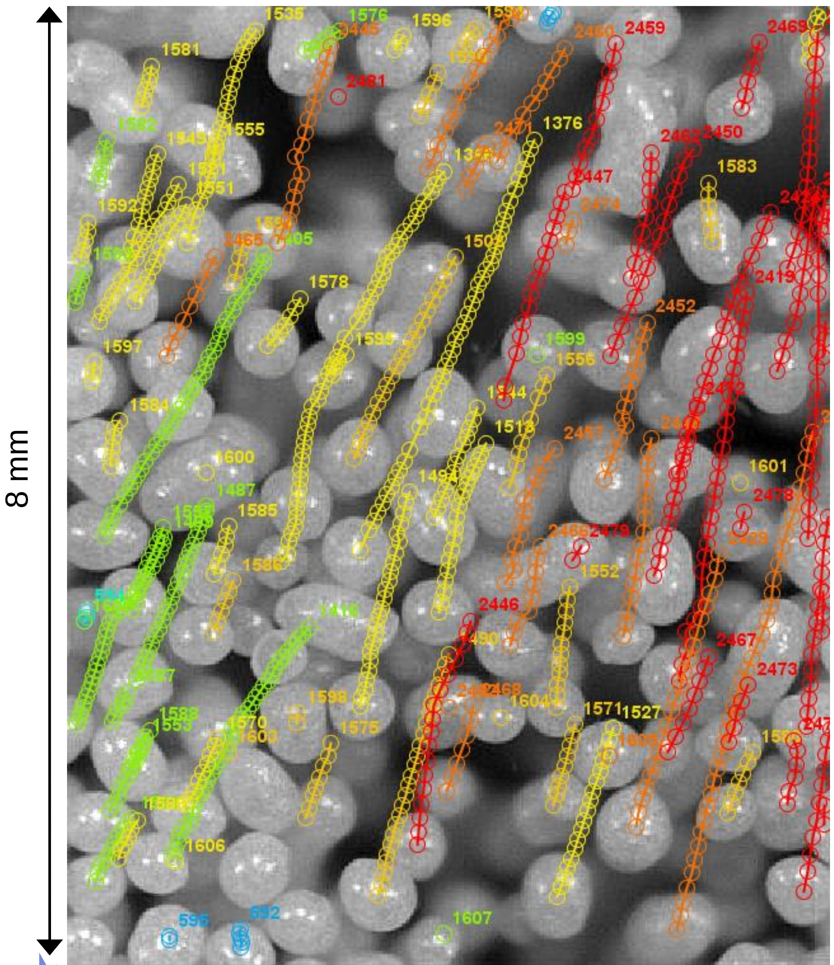
Data Produced by HSPIV:
1. Point Measurement of Individual Particle Motion

- **Small measurement area with dimensions less than about 100 particle diameters. Essentially a point measurement.**
- **Data acquired *automatically*:**
  - ***2D particle trajectories***
  - ***2D velocity along each trajectory***
  - ***Relative particle concentration (# particles in frame / max in any frame)***
  - ***Particle-particle collision parameters (2D)***
  - **Particle rotation (manual analysis only)**
- **Very high accuracy. Measurement uncertainty for velocity is $\leq$ +1%. Mistakes in trajectory recognition are less than 1 in 10,000**
- **Dynamic range is very high: 10000:1**

Data Produced by HSPIV:
1. Measurement of Individual Particle Motion

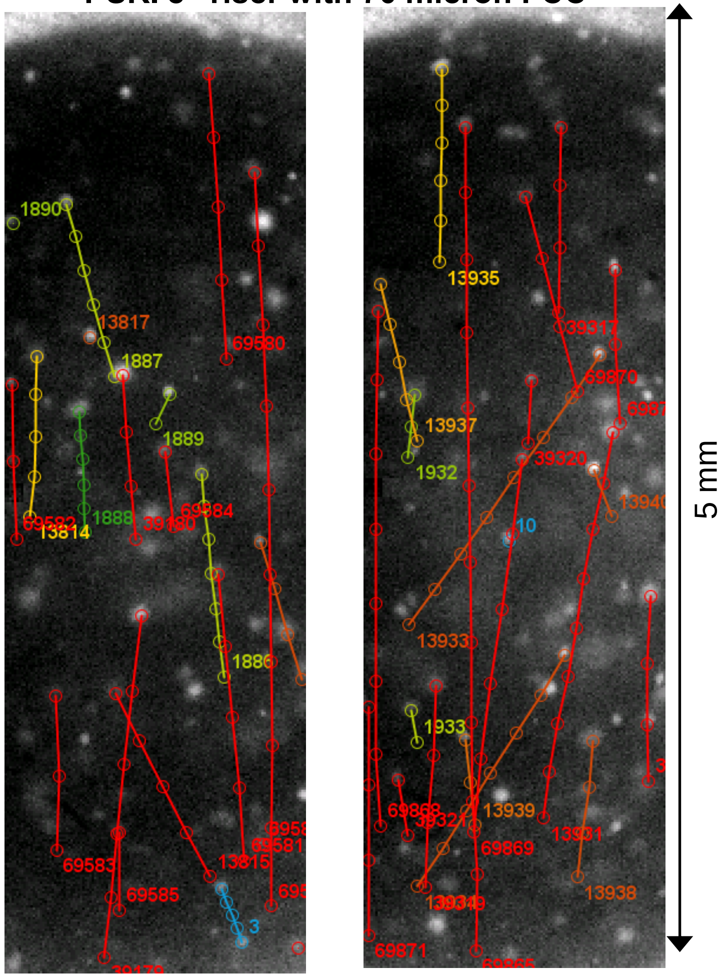
Measurement at riser wall

NETL 12" dia. riser. 750 micron HDPE.



Measurement at riser centerline

PSRI 8" riser with 70 micron FCC



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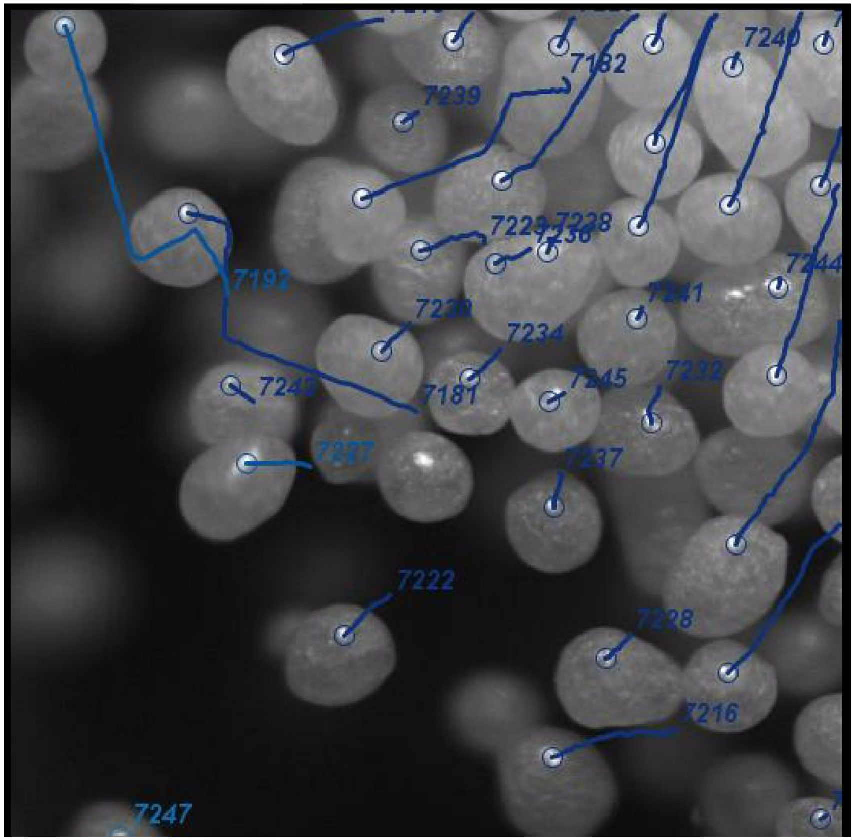
Data Produced by HSPIV:
1. Examples of Individual Particle Motion

- **High speed video showing individual particle measurement over small measurement area**
- [F:\NETL_MPF_Workshop_5-3-10\Frank's_Presentation\Graphics_to_show\Ind_Part_Meas\NETL_HSPIV_Ex\Movie_Individual_Part_Motion_MFP_Workshop.avi]()



Data Produced by HSPIV:
2. Large Area Mapping of Particle Motion

- **Lange sample area: > 1000 particle diameters.**
  Allows measurement of large flow structures and gradients of velocity and concentration
- **Data acquired automatically:**
  - ***2D particle trajectories***
  - ***2D velocity along each trajectory***
  - ***Relative particle concentration***
- **Can calculate maps of GT and gradients of velocity or conc., etc**

Data Produced by HSPIV:
2. Large Area Mapping of Particle Motion

- **High speed video example:**
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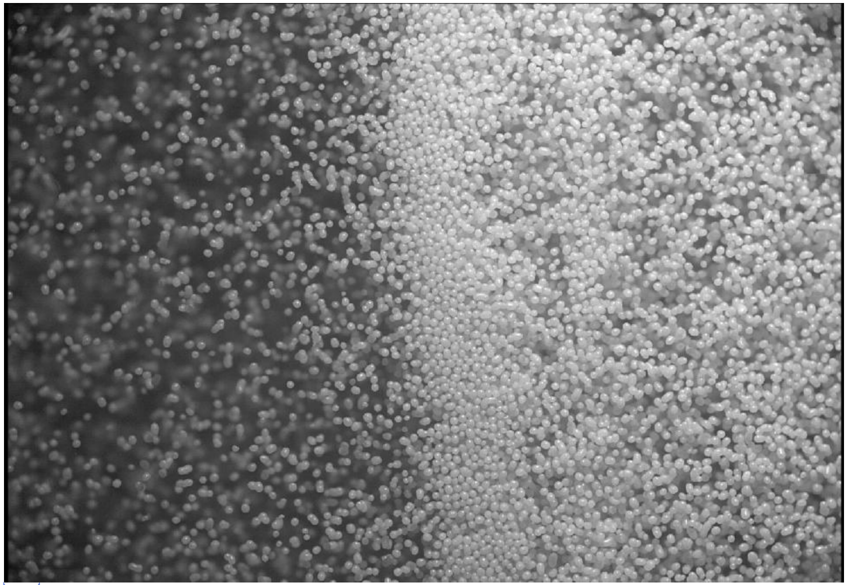
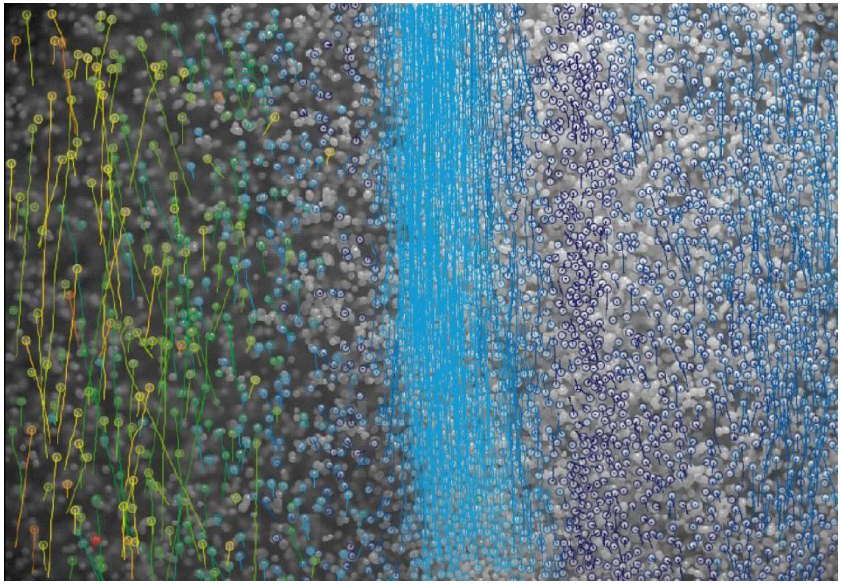
- **F:\NETL_MPF_Workshop_5-3-10\Frank's_Presentation\Graphics_to_show\Large_Area_Mapping\Std_Cond_18_JP352_with_traj_tracking.avi**





Tracking Random Motion
Example: Trajectory Recognition in Random Motion

- **Software capabilities:** ***Tracking random motion***
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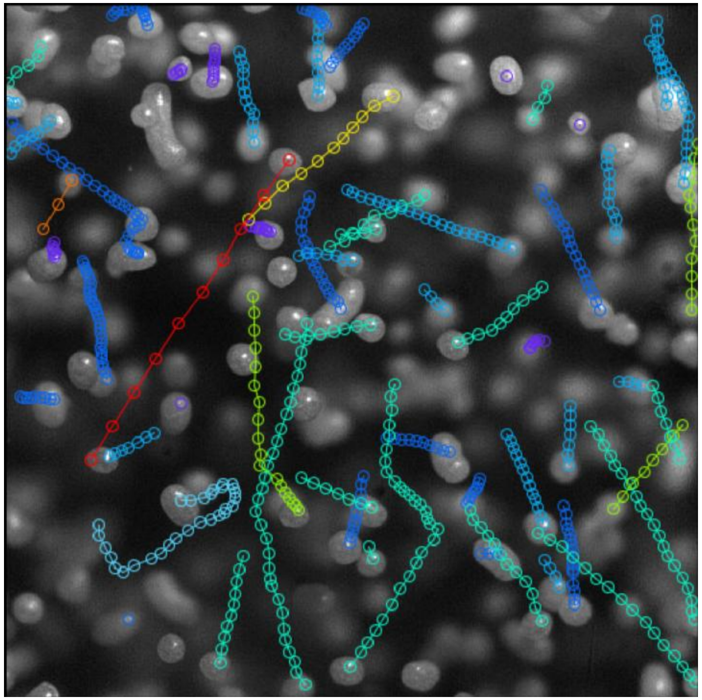
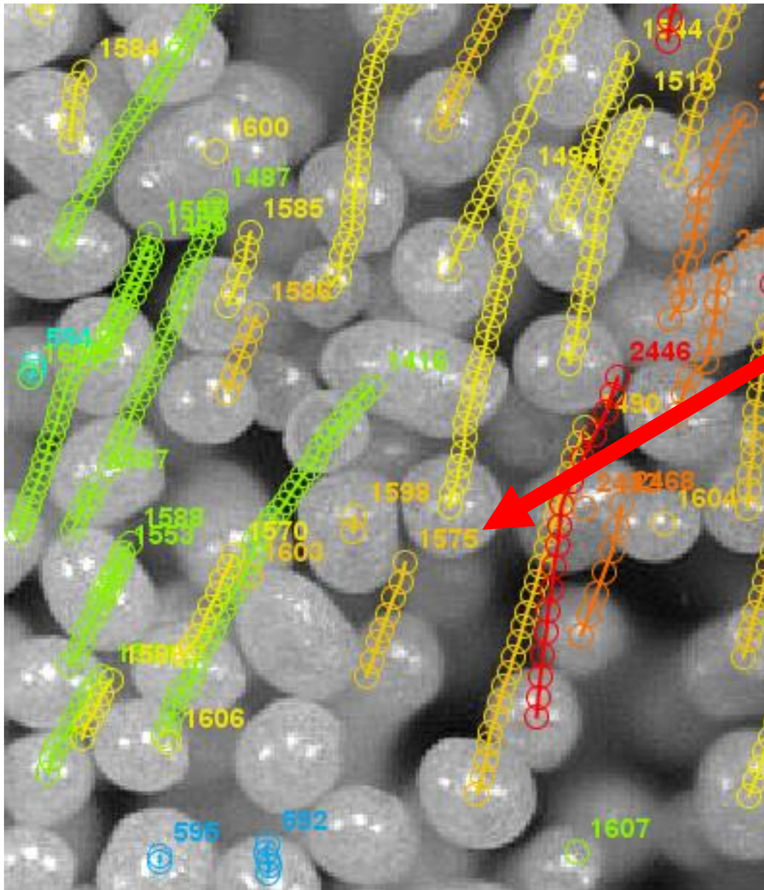
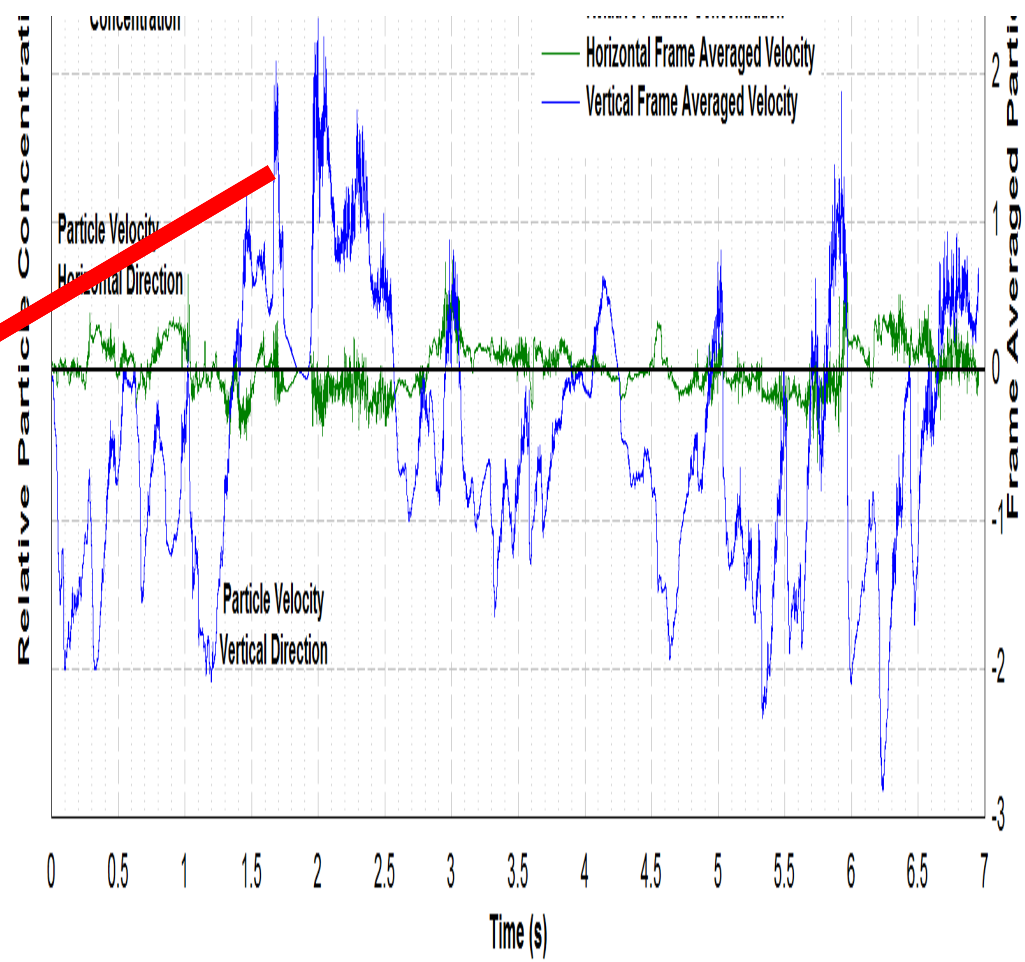


Data Produced by HSPIV:
3. HS videos with trajectories identified for comparison with data

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.





Comparison of NETL HSPIV with other particle velocity measurement techniques for riser flow conditions

PI's	Meas. Technique	Data	Data Rate	Uncertainty/ Dynamic Range
Tartan, Gidaspow, et al.	streak PTV with color coding for direction	2D traj., velocity; # conc.	**< 500 vectors/sec**	> ± 10% / low dynamic range ~10:1
NETL et al.	LDV	2D traj., velocity; # conc per unit time	**< 500 vectors/sec**	< ± 1% / high dynamic range
Many others	Various particle tracking methods (radioactive tagging, color coding, etc.)	2D traj., velocity; # conc.	**< 500 vectors/sec**	± 1 – 25%
NETL	***HSPIV***	*See previous slide*	***up to 1 million vectors/s always > 100,000 /s***	*< ± 1% / 10,000:1*

Comparison of NETL HSPIV with other particle velocity measurements techniques

- Previous techniques have sampling rates < 500 samples/sec, so frequencies in velocity signal can be resolved up to 250 Hz (Nyquist-Shannon)
- Our measurements and KE theory (You et al.) show that most of the frequencies of the random fluctuating component of velocity in risers are higher than 250 Hz
- Previous techniques do not have sample rates high enough to resolve the random fluctuating component of velocity
- ***NETL HSPIV system, with sampling rates up to 1 million/sec, fully resolves all temporal scales of particle velocity, including the random fluctuating velocity, which is the highest frequency component***
- ***NETL HSPIV system is first to completely and accurately measure granular temperature, particle stress, etc.***

Results from Applications of NETL HSPIV System

RESULTS to be shown today:

- ***Example data for particle velocity and concentration***
- ***Example data for accurate measurements of granular temperature***
- ***A new view of riser flow behavior: unsteady jets***
- ***A new view of clustering in fluidized beds and risers***

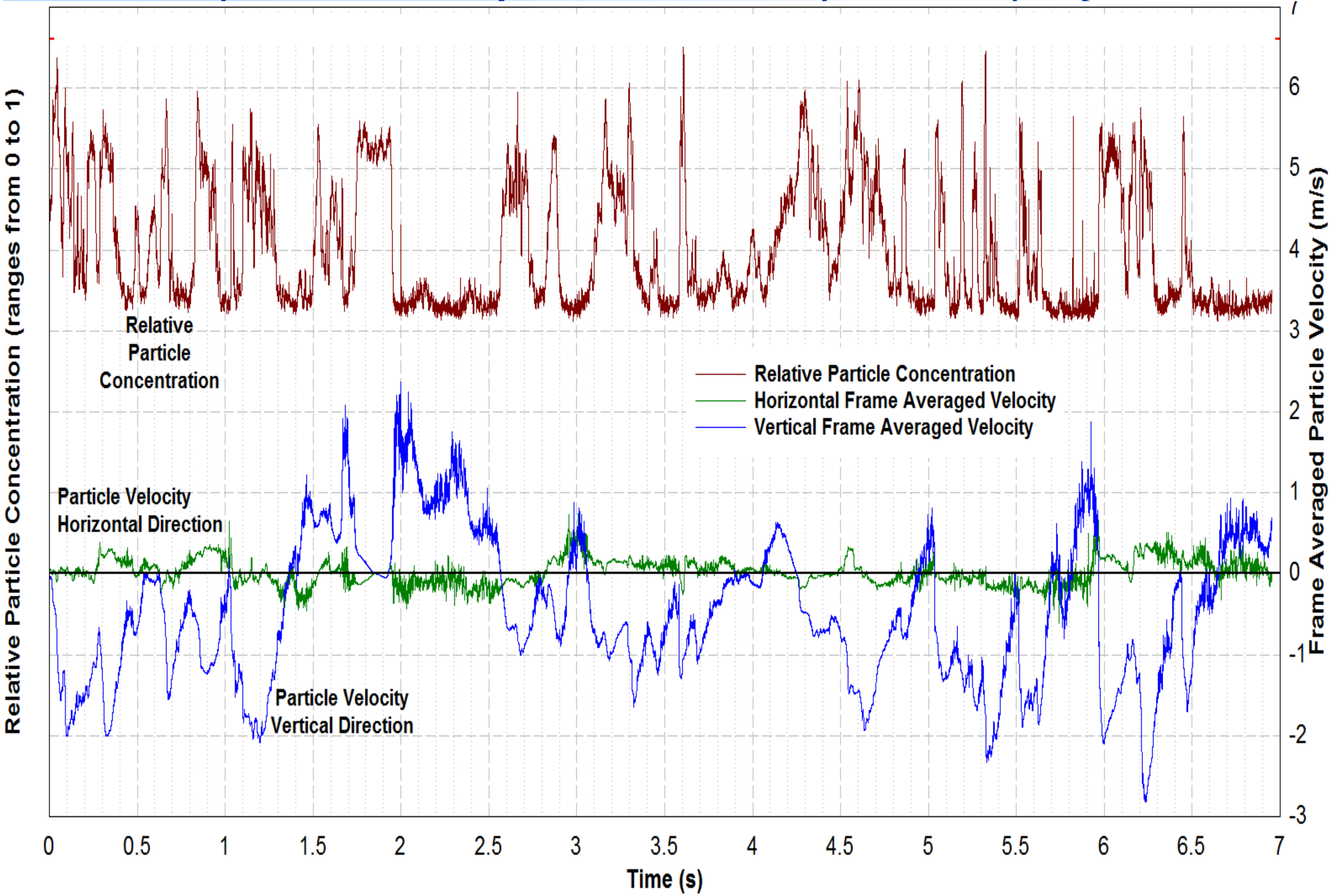
HSPIV System Applied to Many High Concentration Particle Flows at NETL and PSRI

- Fluidized beds up to 2 ft x 5 ft cross section x 20 ft high (PSRI)
- Riser diameters 8” to 12” diameter risers, with heights up to 70 ft (NETL and PSRI)
- Particle sizes from 30 micron to 750 micron (glass, FCC, HDPE)
- Speeds up to 50 m/s
- Solids flux up to 400 kg/m^2/s

HSPIV Measurement of Local-Averaged Particle Velocity and Concentration

NETL 12" riser: 750 micron HDPE; superficial gas velocity = 6.6 m/s, <u>***solids flux = 20 kg/m2/***</u>

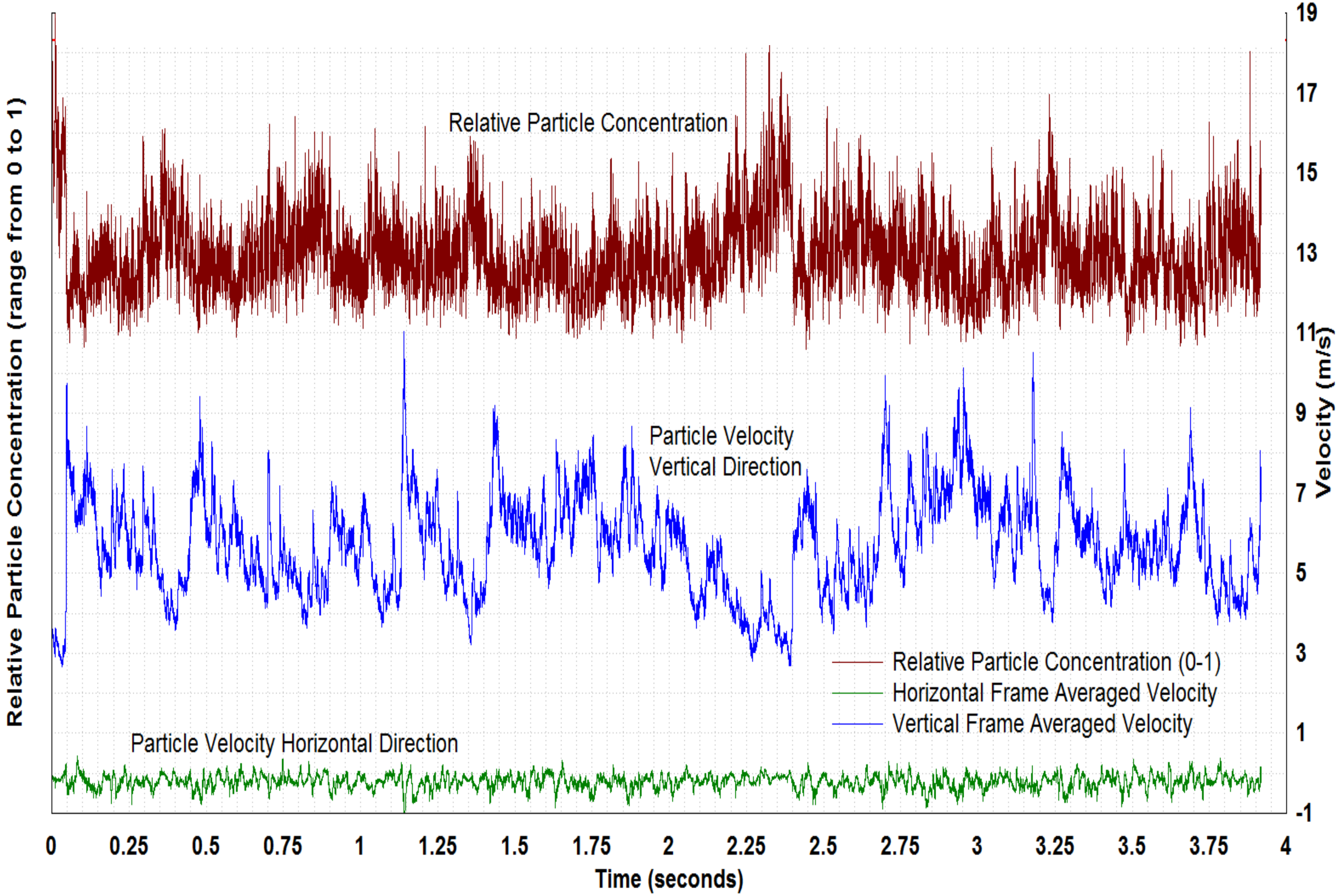
Data for 2.4 million velocity vectors shown; 12,500 frames/sec ; 4 μs exposure



Local-Averaged Particle Velocity and Concentration

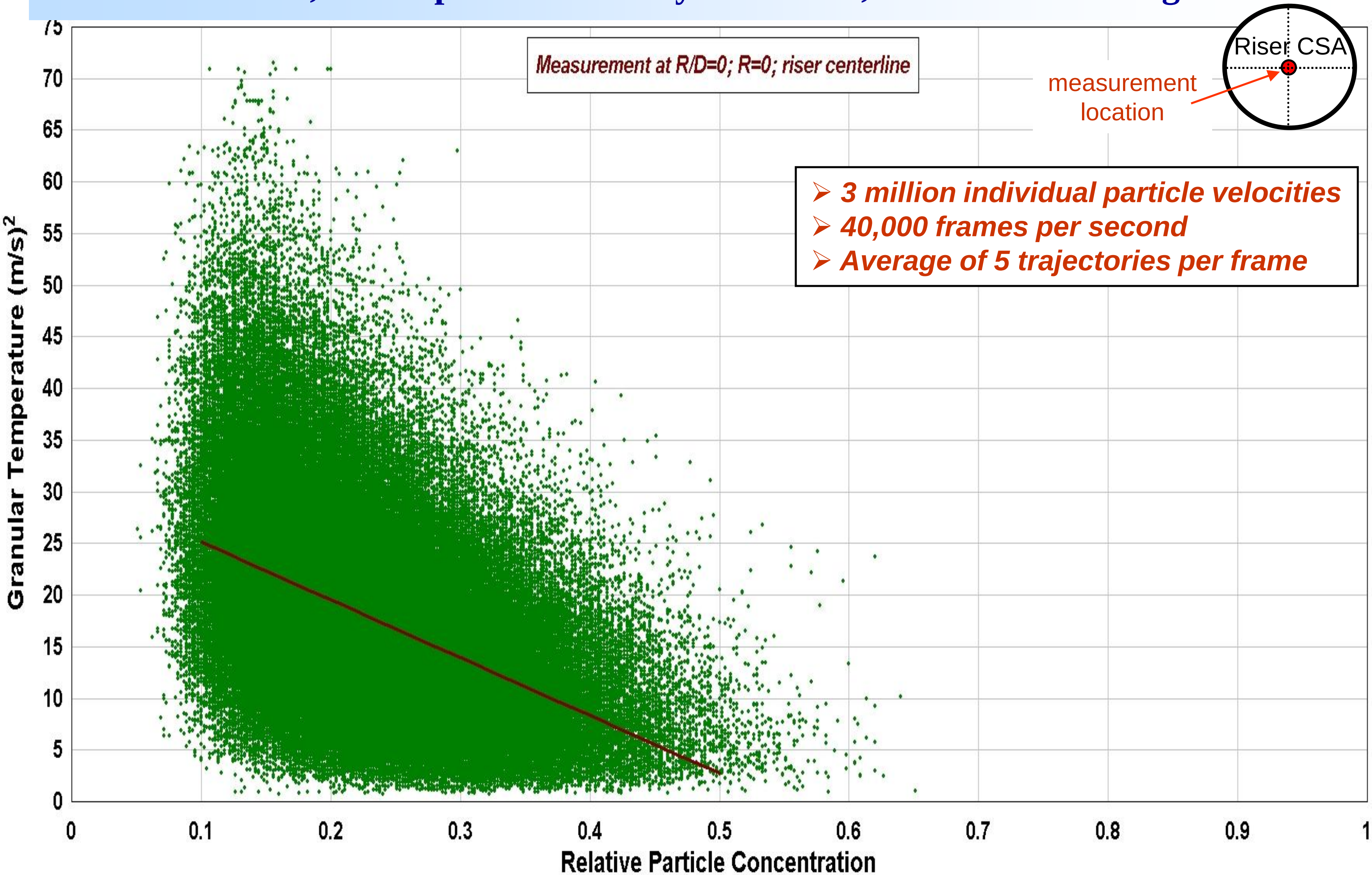
PSRI 8" Riser; 70 micron FCC; superficial gas velocity = 18.3 m/s, ***solids flux = 380 kg/m2/s***

Data for 3 million velocity vectors shown ; 40,000 frames/sec ; 4 μs exposure



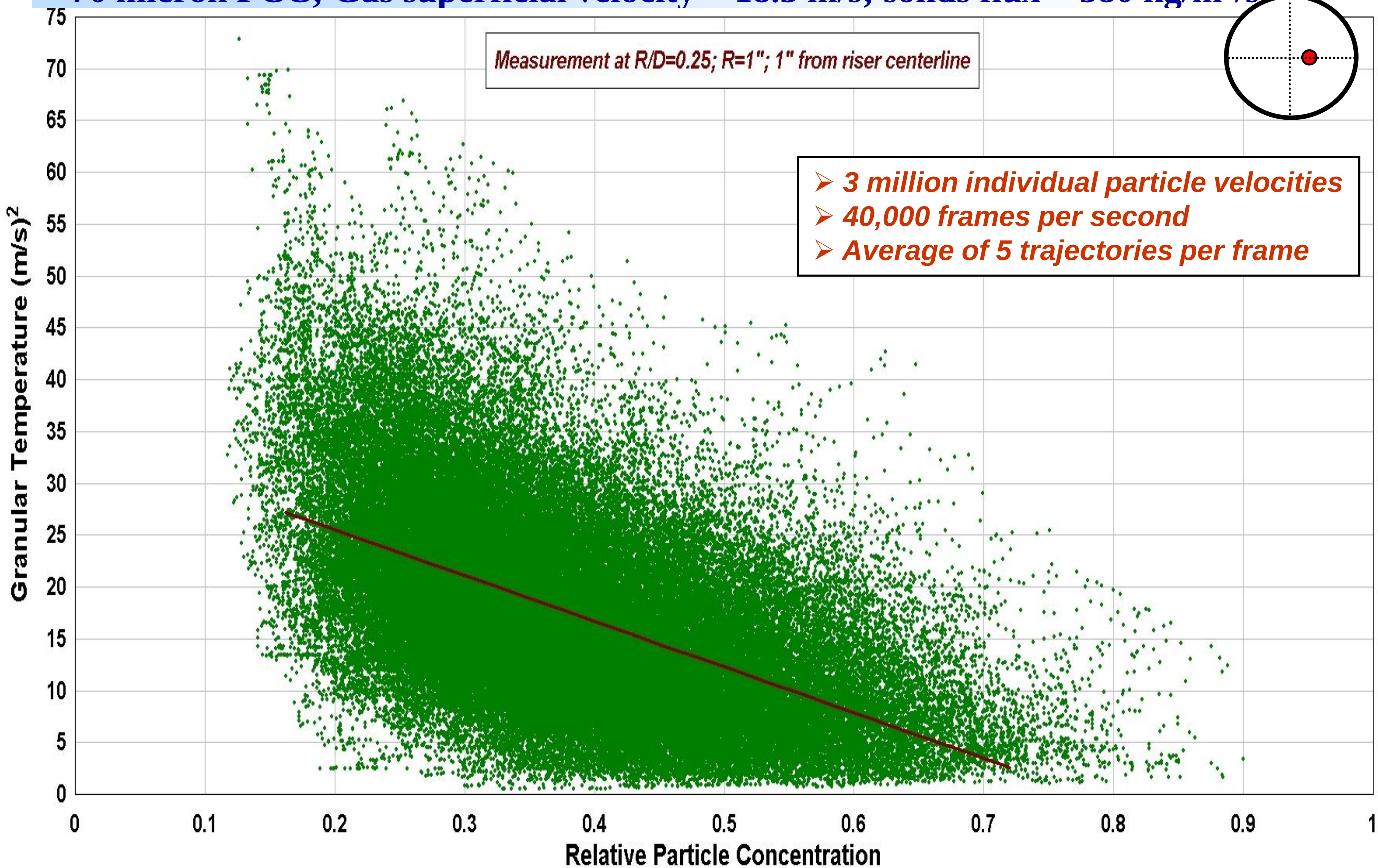
Granular Temperature in PSRI 8" Riser

70 micron FCC; Gas superficial velocity = 18.3 m/s; solids flux = 380 $kg/m^2/s$



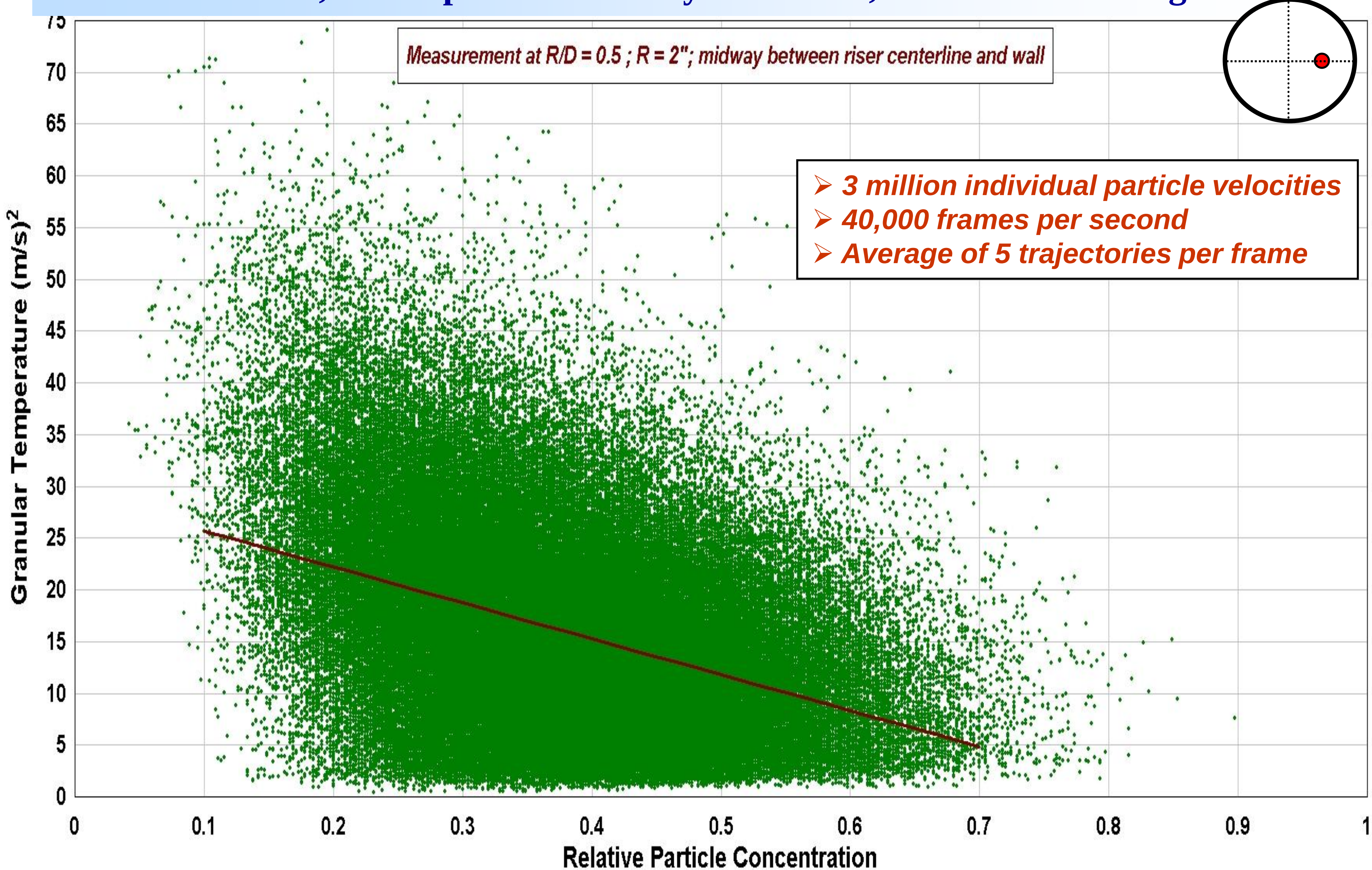
Granular Temperature in PSRI 8” Riser

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



Granular Temperature in PSRI 8" Riser

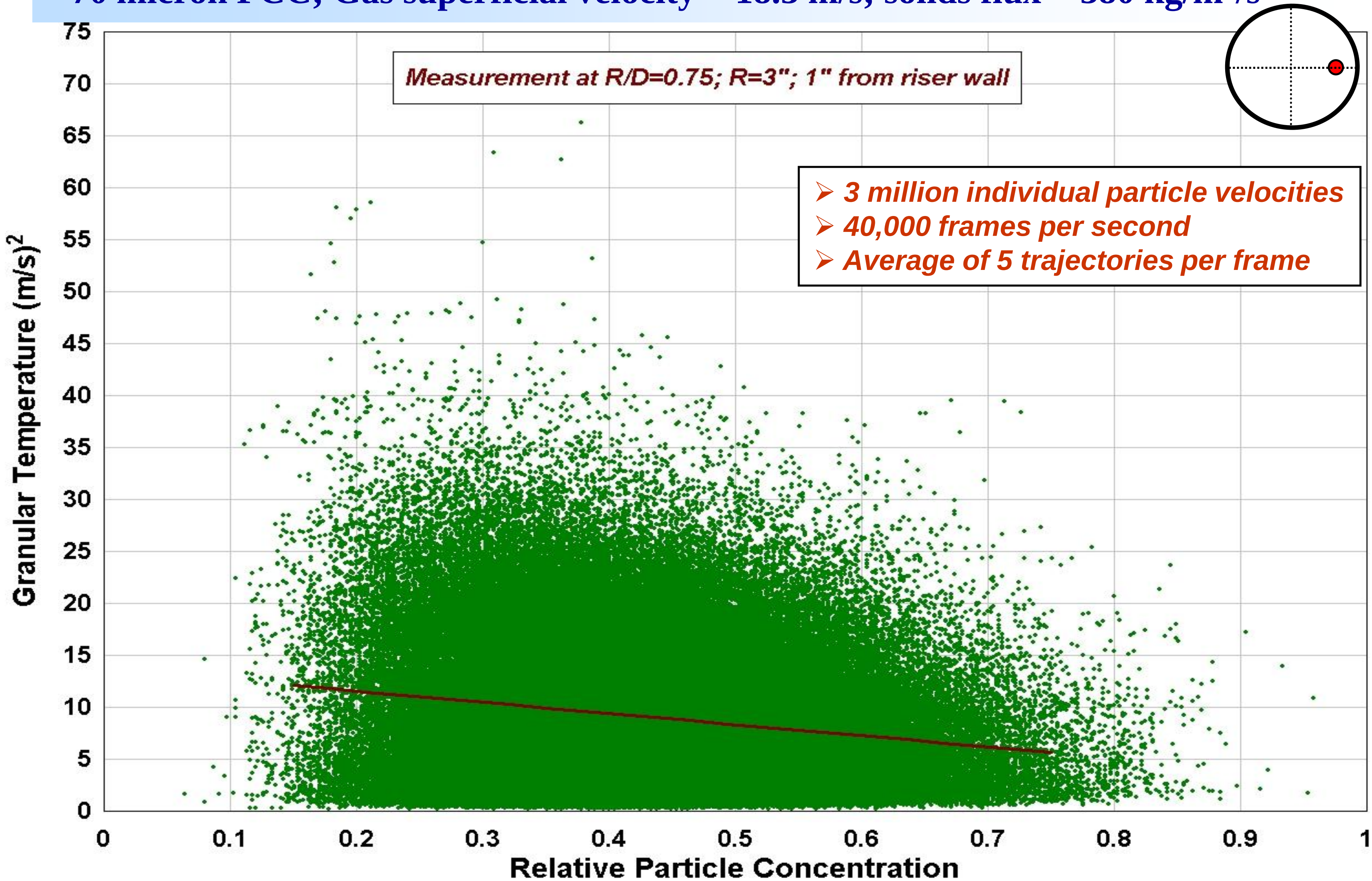
70 micron FCC; Gas superficial velocity = 18.3 m/s; solids flux = 380 kg/m²/s



- *3 million individual particle velocities*
- *40,000 frames per second*
- *Average of 5 trajectories per frame*

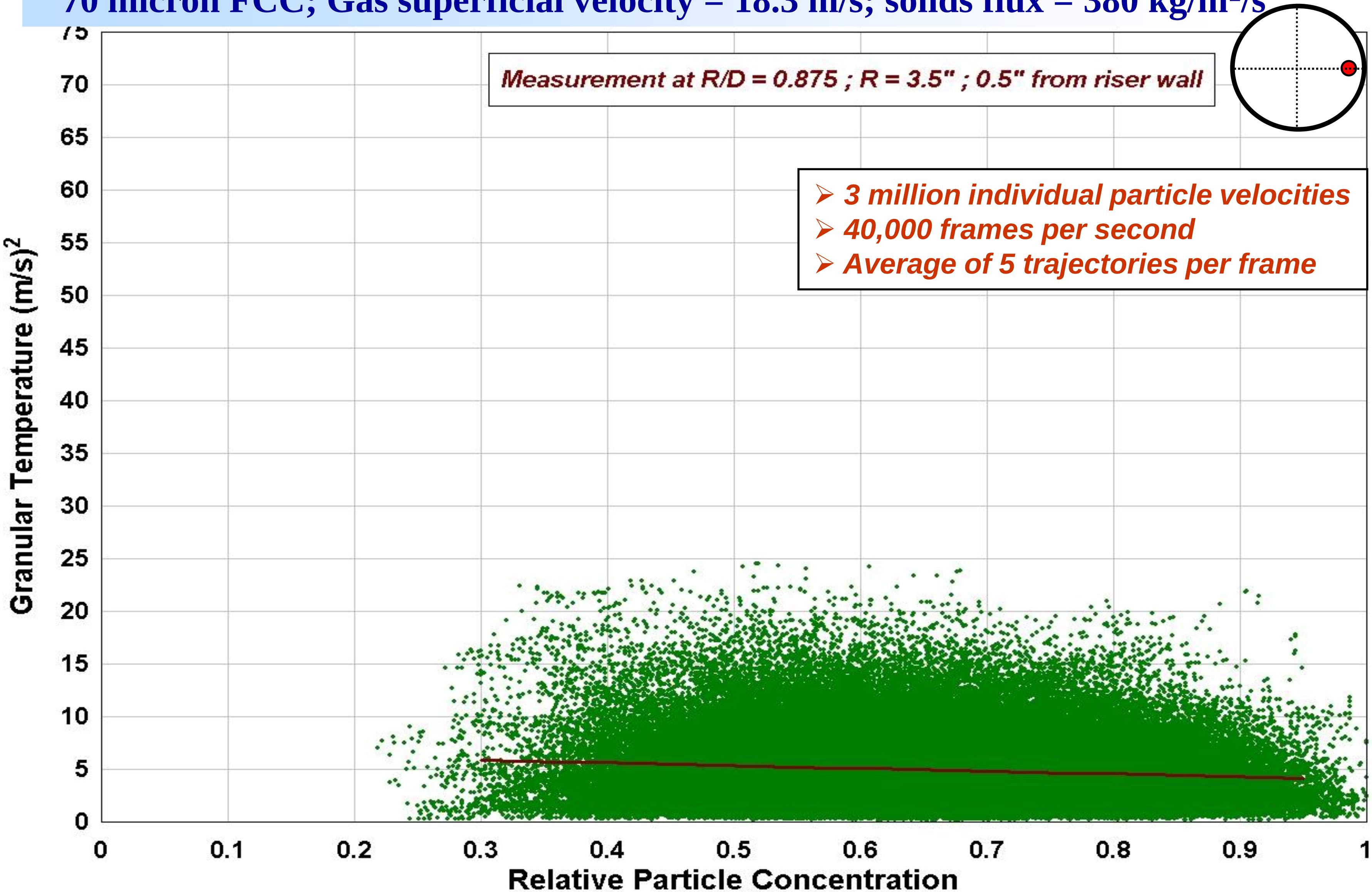
Granular Temperature in PSRI 8" Riser

70 micron FCC; Gas superficial velocity = 18.3 m/s; solids flux = 380 kg/m^2/s



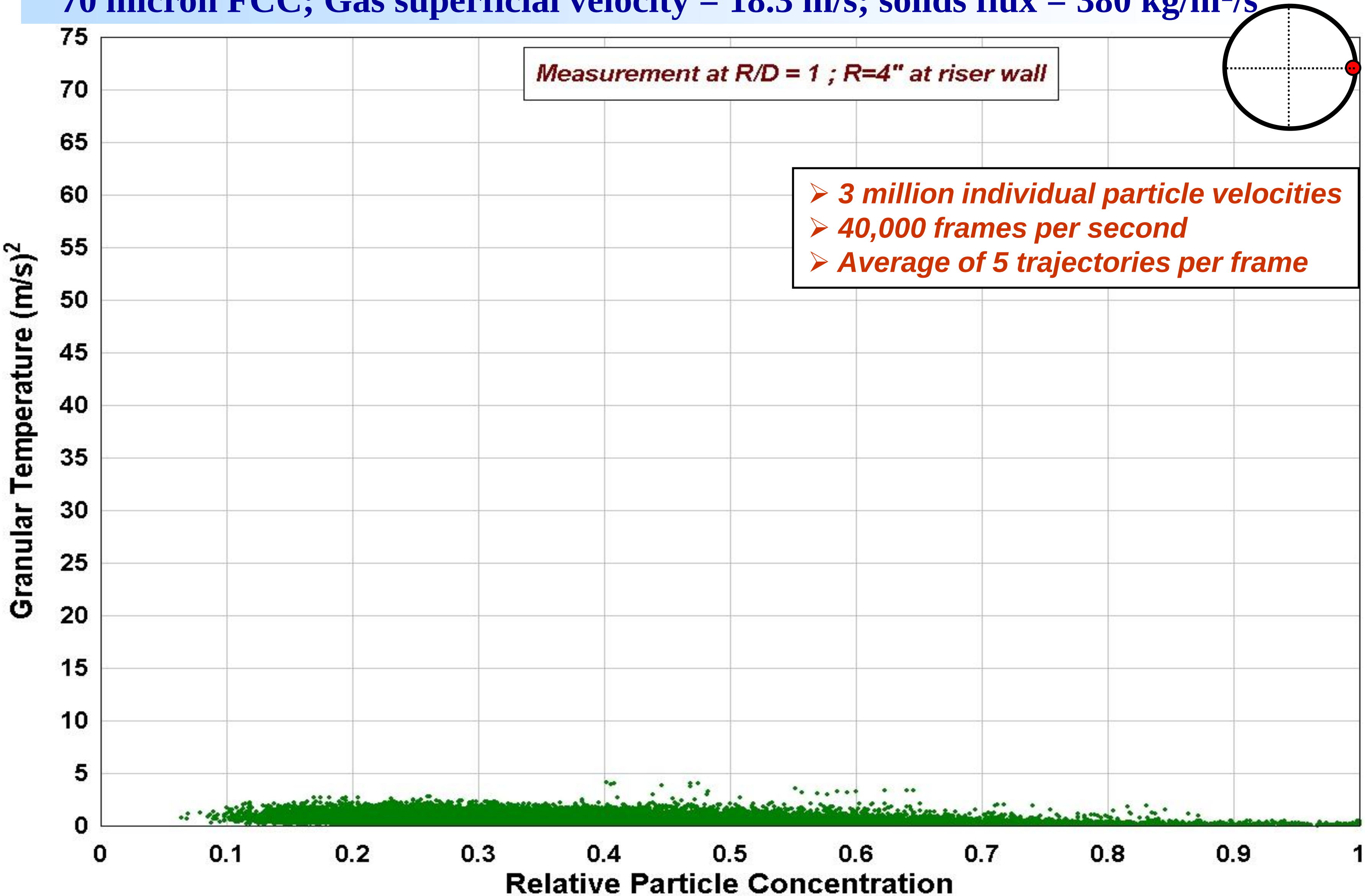
Granular Temperature in PSRI 8” Riser

70 micron FCC; Gas superficial velocity = 18.3 m/s; solids flux = 380 kg/m^2/s



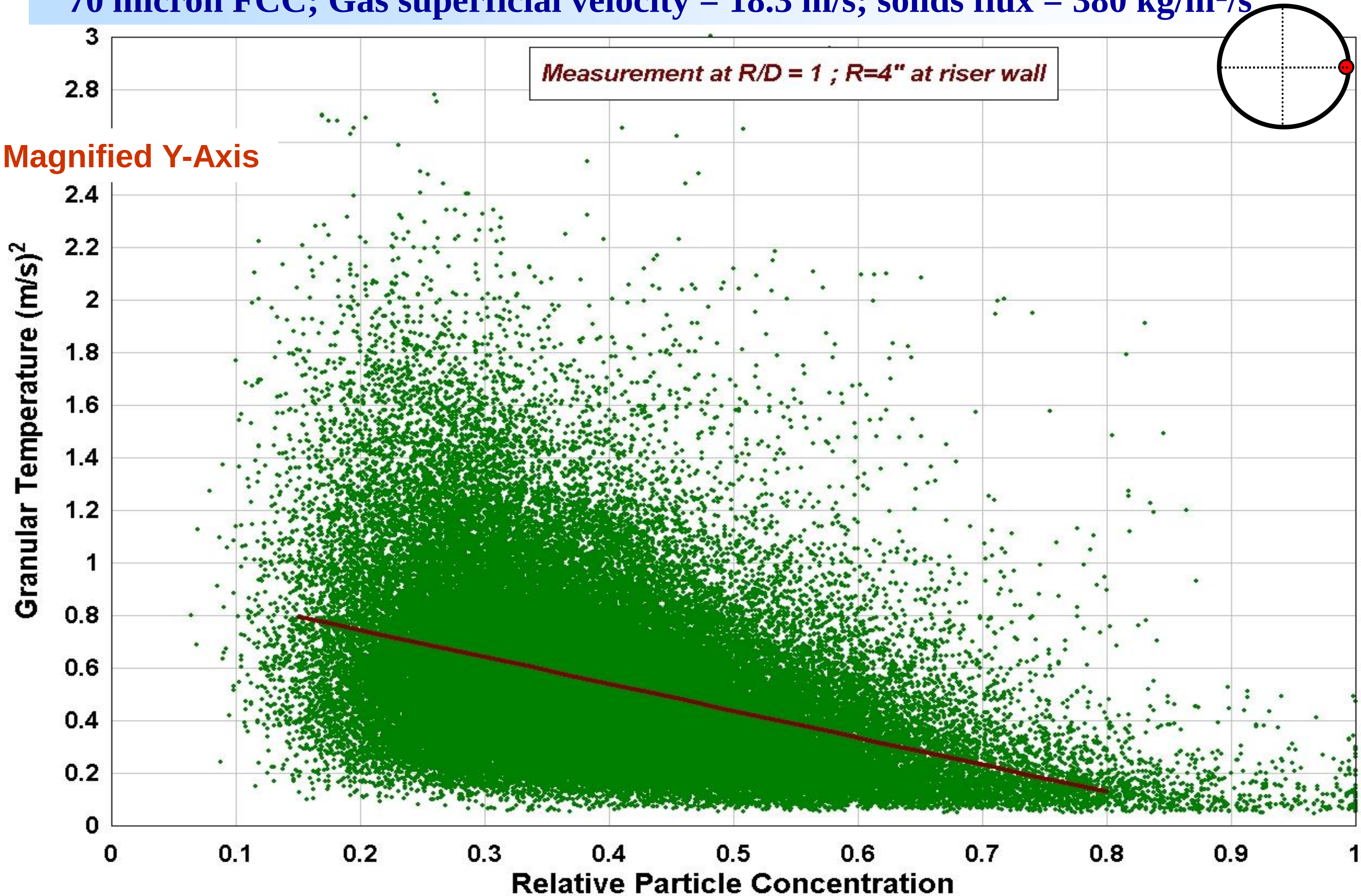
Granular Temperature in PSRI 8" Riser

70 micron FCC; Gas superficial velocity = 18.3 m/s; solids flux = 380 kg/m^2/s

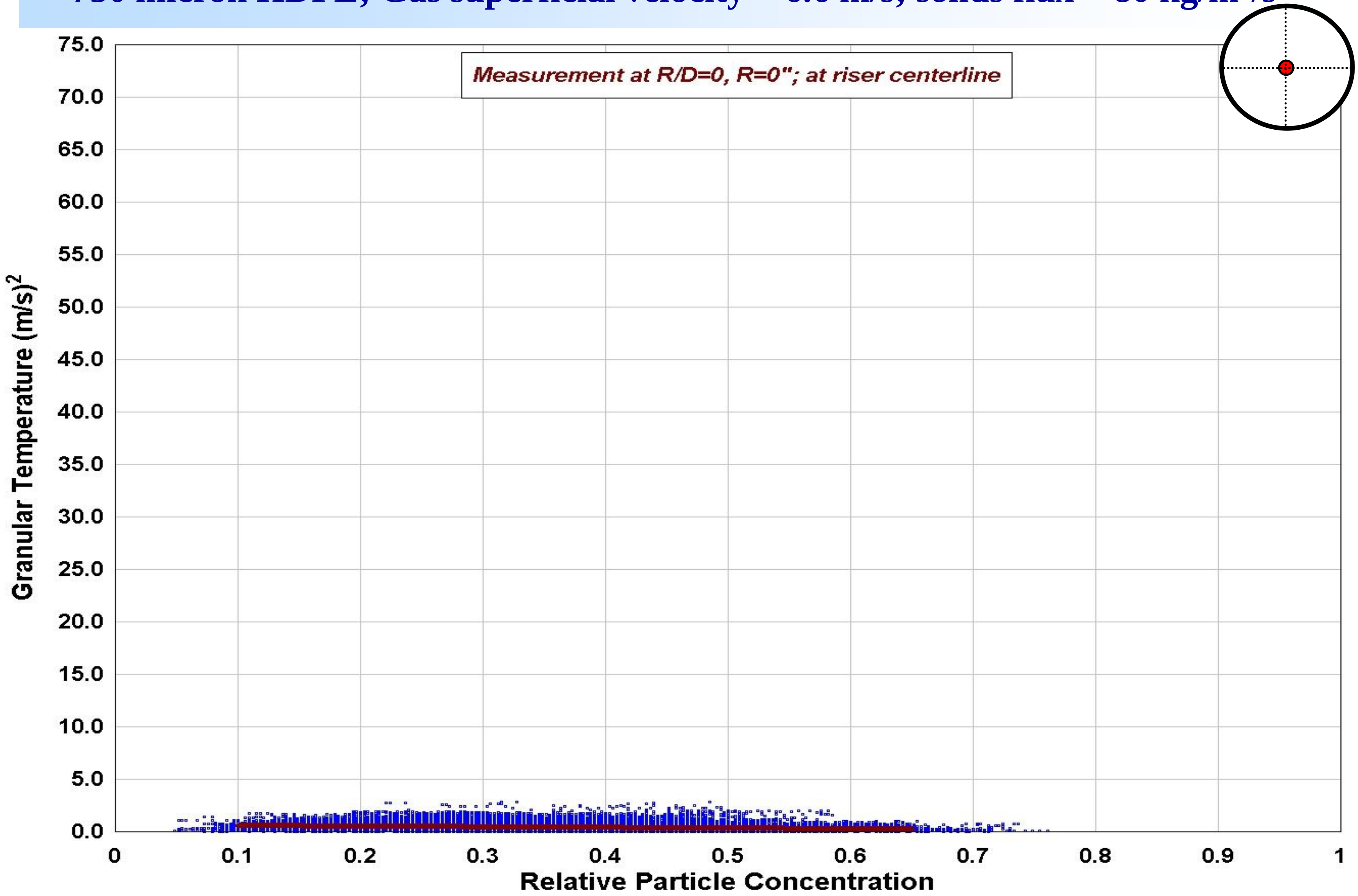


Granular Temperature in PSRI 8” Riser

70 micron FCC; Gas superficial velocity = 18.3 m/s; solids flux = 380 kg/m^2/s



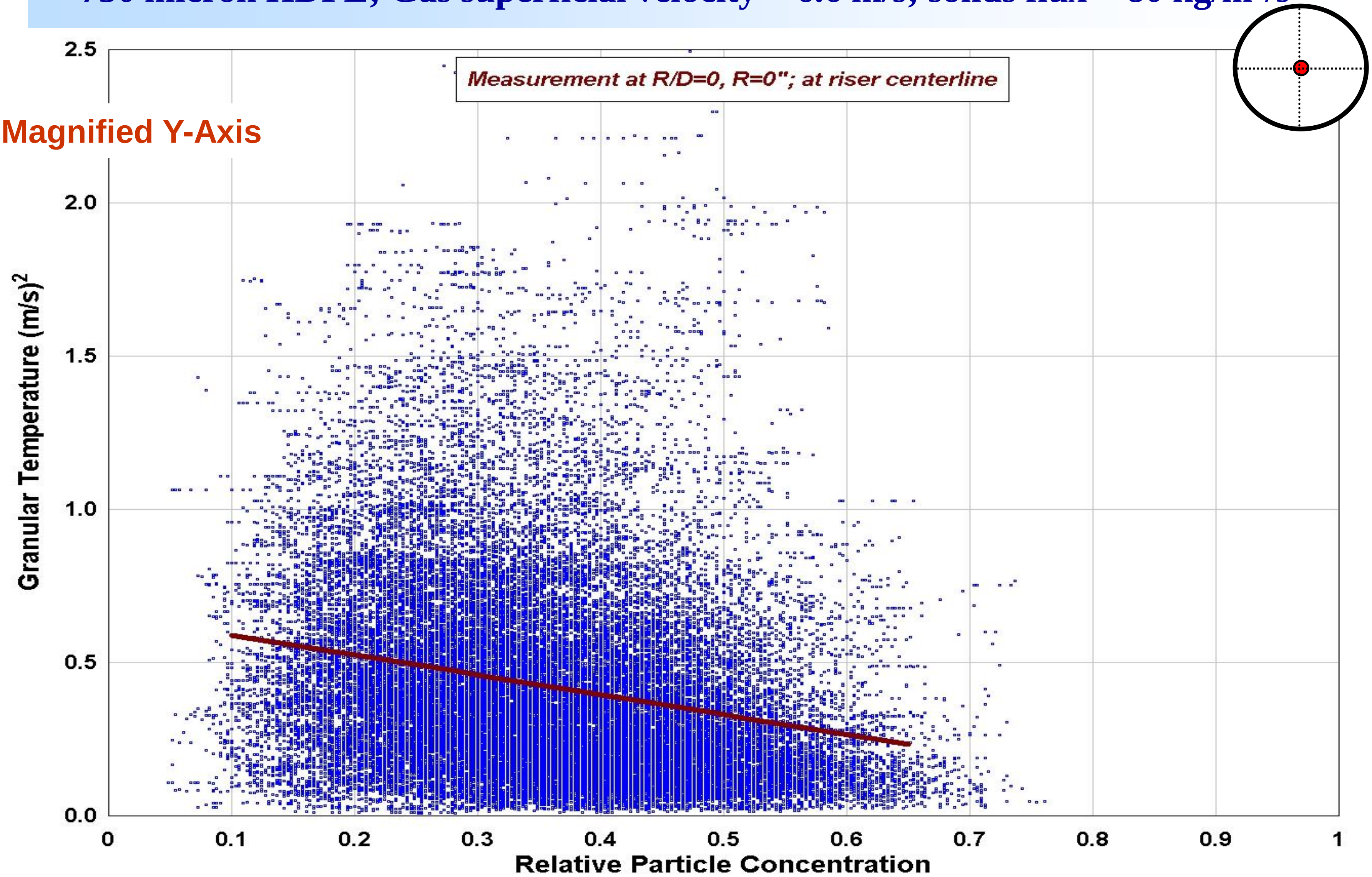
Granular Temperature in NETL 12" Riser
750 micron HDPE; Gas superficial velocity = 6.6 m/s; solids flux = 80 kg/m²/s



Granular Temperature in NETL 12" Riser

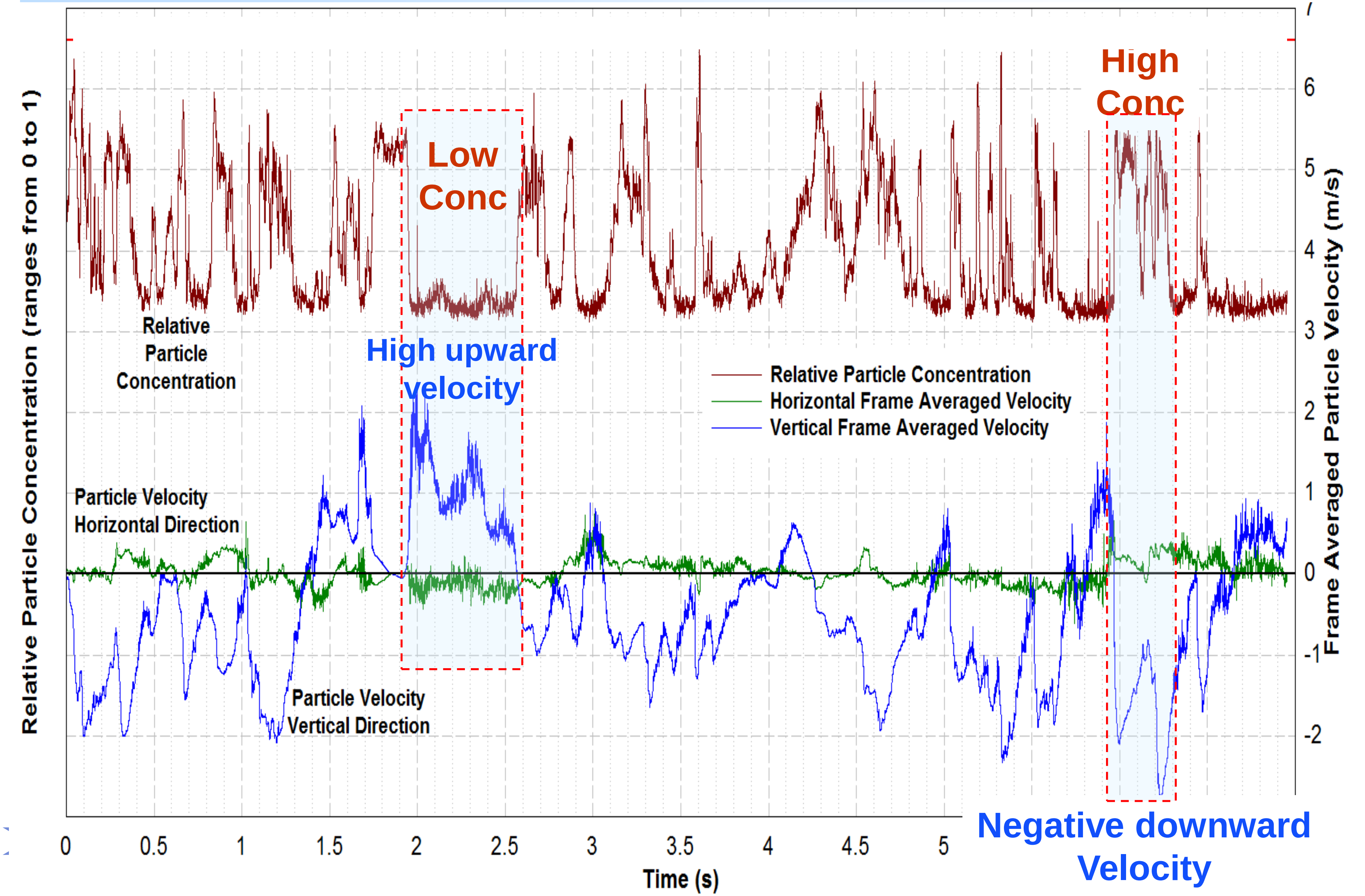
750 micron HDPE; Gas superficial velocity = 6.6 m/s; solids flux = 80 kg/m²/s

Magnified Y-Axis



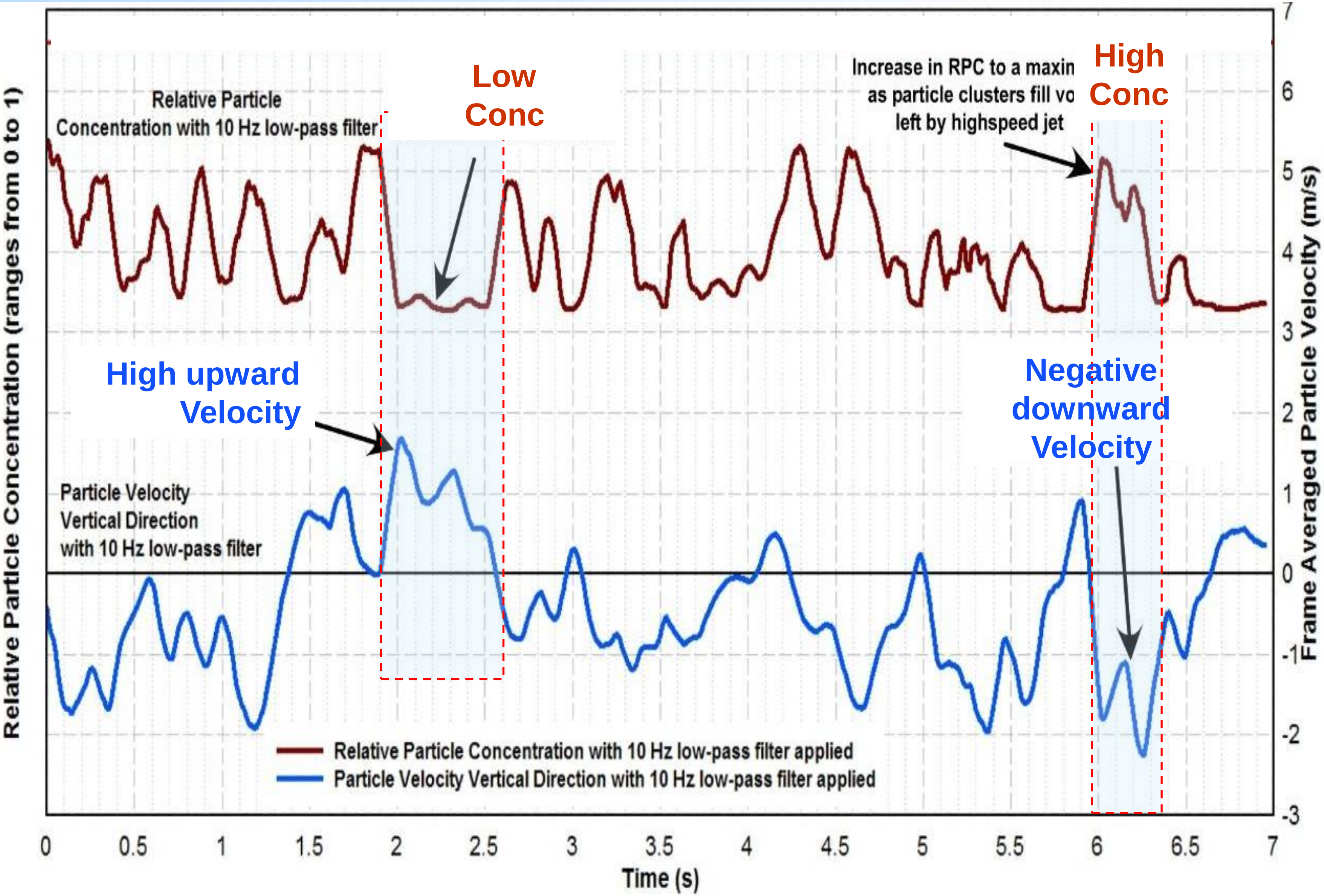
Unsteady Jet Behavior in Risers

Correlation between Relative Velocity and Concentration: *Unsteady Jet Behavior*



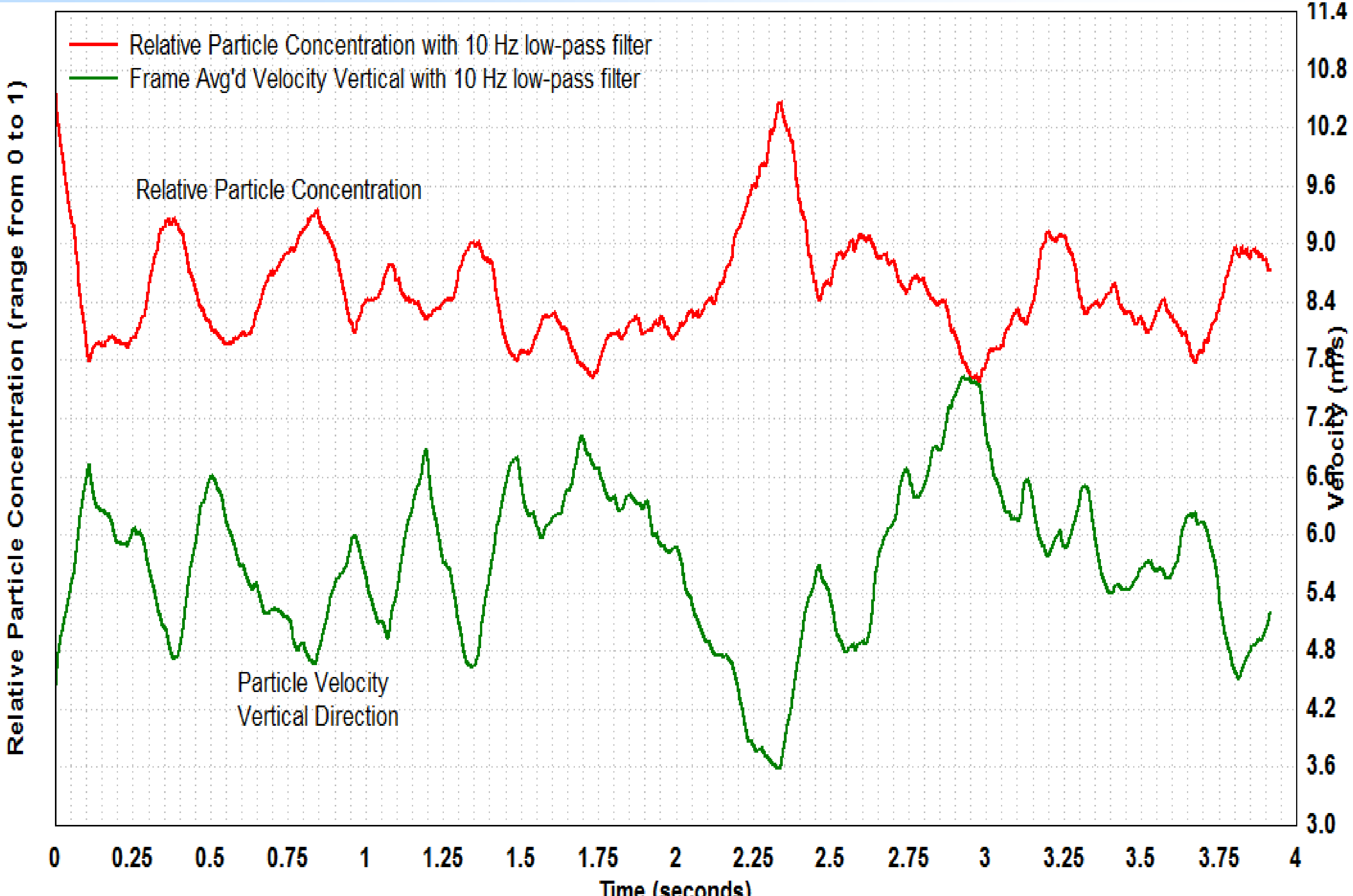
Low-Pass Filter Applied to Reveal Large Flow Structures

NETL 12” Riser; 750 mic HDPE; superficial gas velocity = 6.6 m/s, s**olids flux = 80 kg/m²/s**



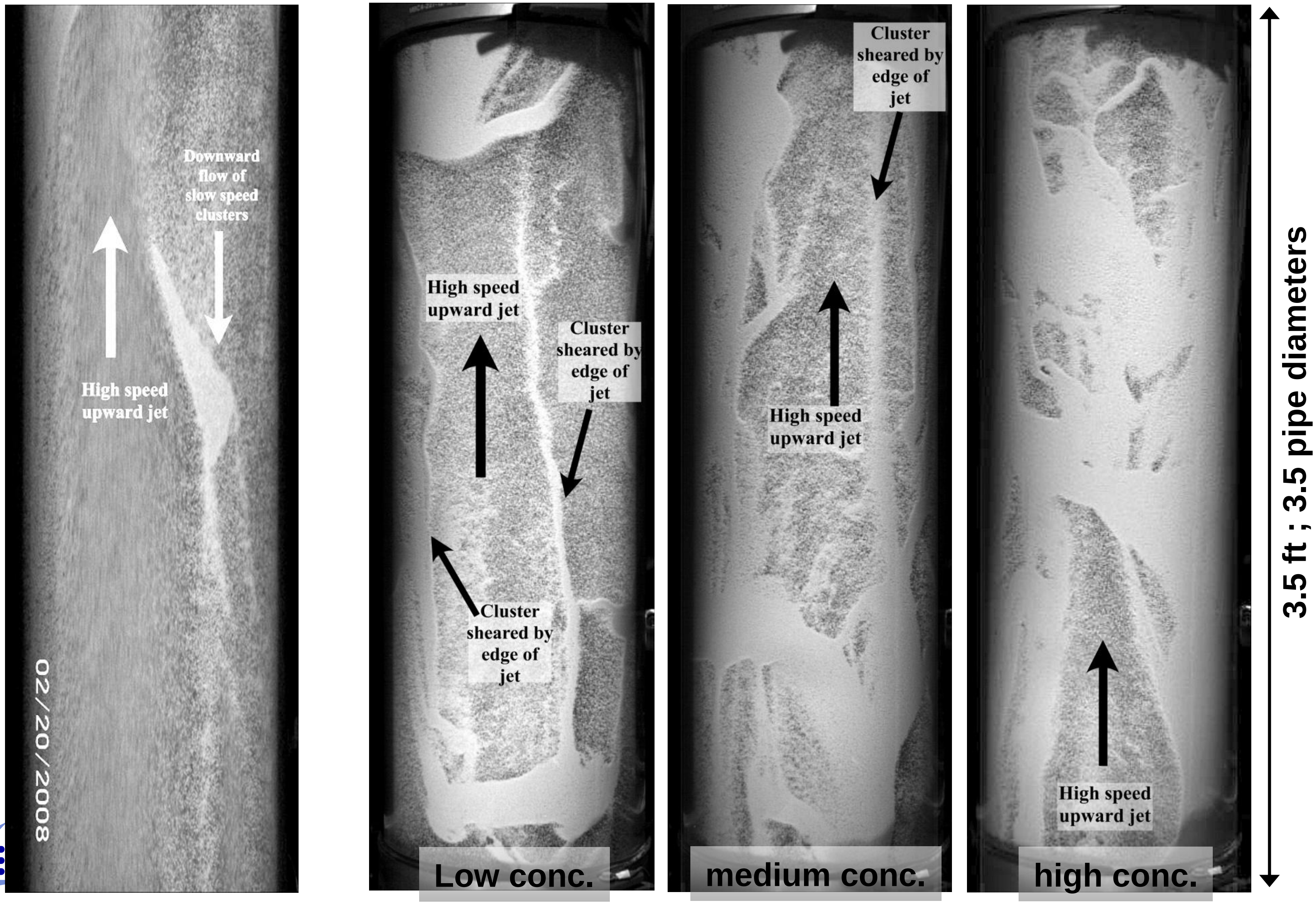
Low-Pass Filter Applied to Reveal Large Flow Structures

PSRI 8 in Riser with 70 micron FCC particles, Superficial gas vel of 9.4 m/s, solids flux = 80 kg/m^2/s



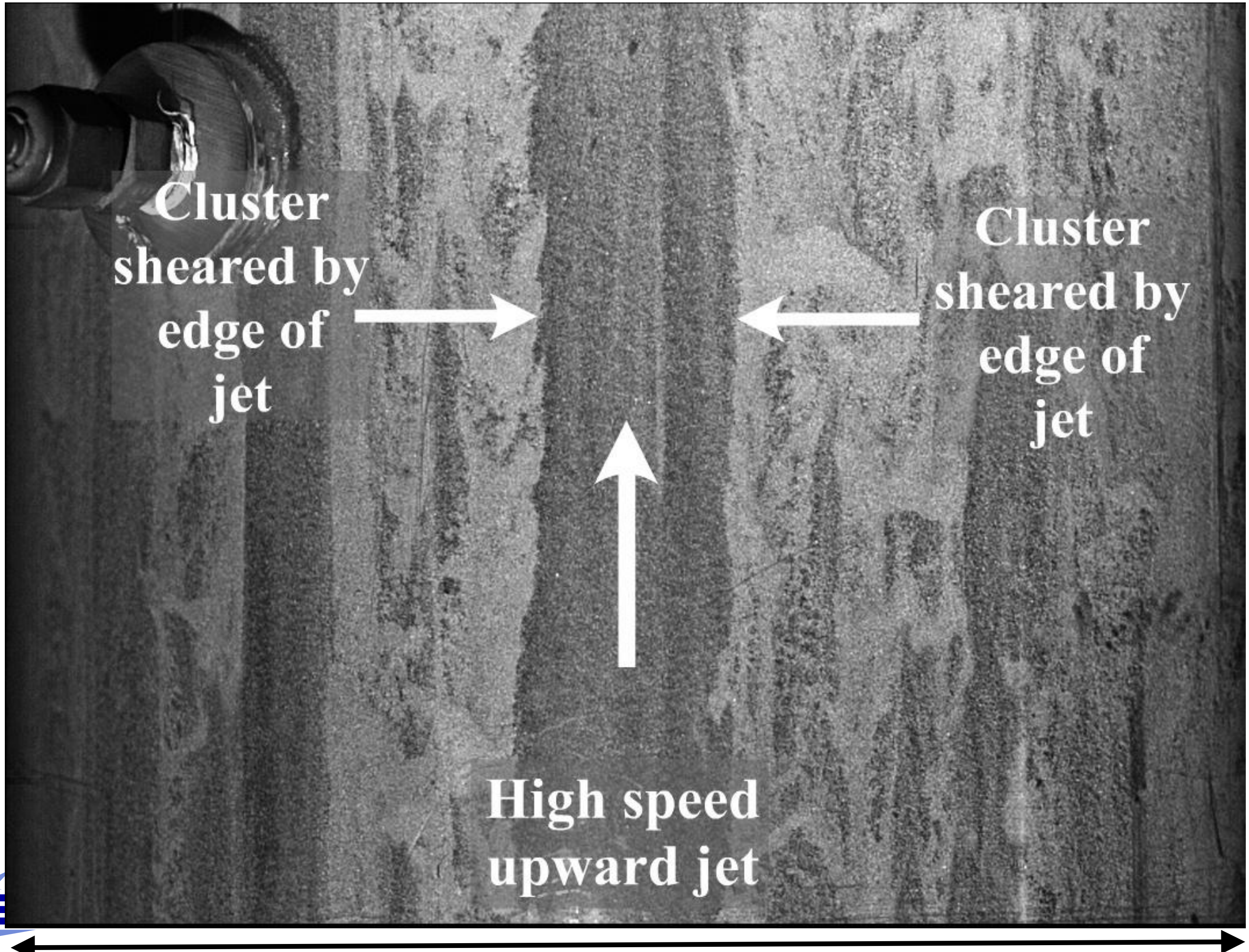
Unsteady Jet Against Riser Wall and Clustering Behavior

NETL Riser with 750 micron HDPE Particles



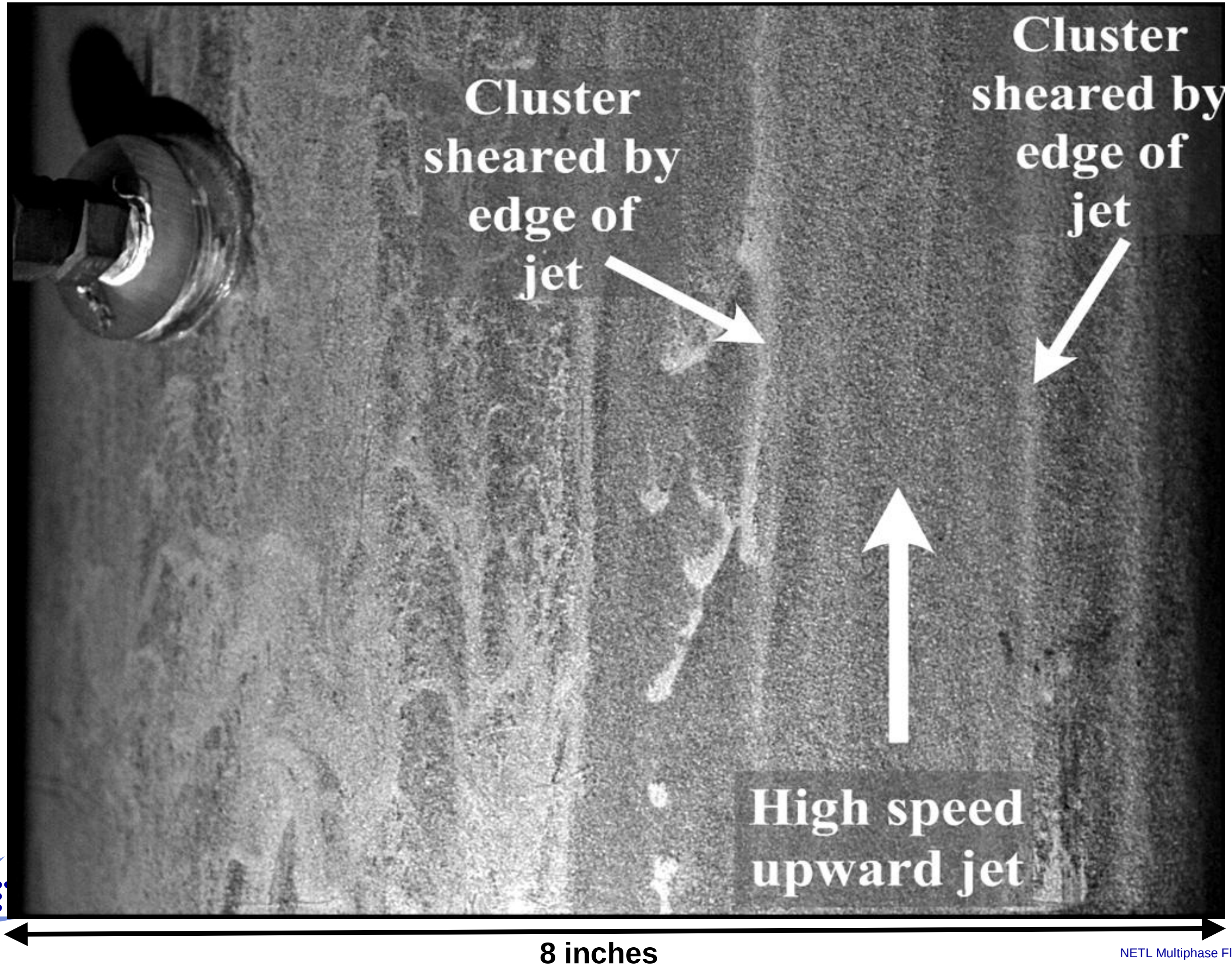
Unsteady Jet Against Riser Wall and Clustering Behavior

PSRI 8" Riser with 70 micron FCC ; solids flux = 50 kg/m²/s ; 30 μs exposure



Unsteady Jet Against Riser Wall and Clustering Behavior

PSRI 8” Riser with 70 micron FCC ; solids flux = 380 kg/m^2/s ; 30 μs exposure



Unsteady Jet Against Riser Wall and Clustering Behavior
High Speed Video Examples

Unsteady high speed jet example in NETL riser

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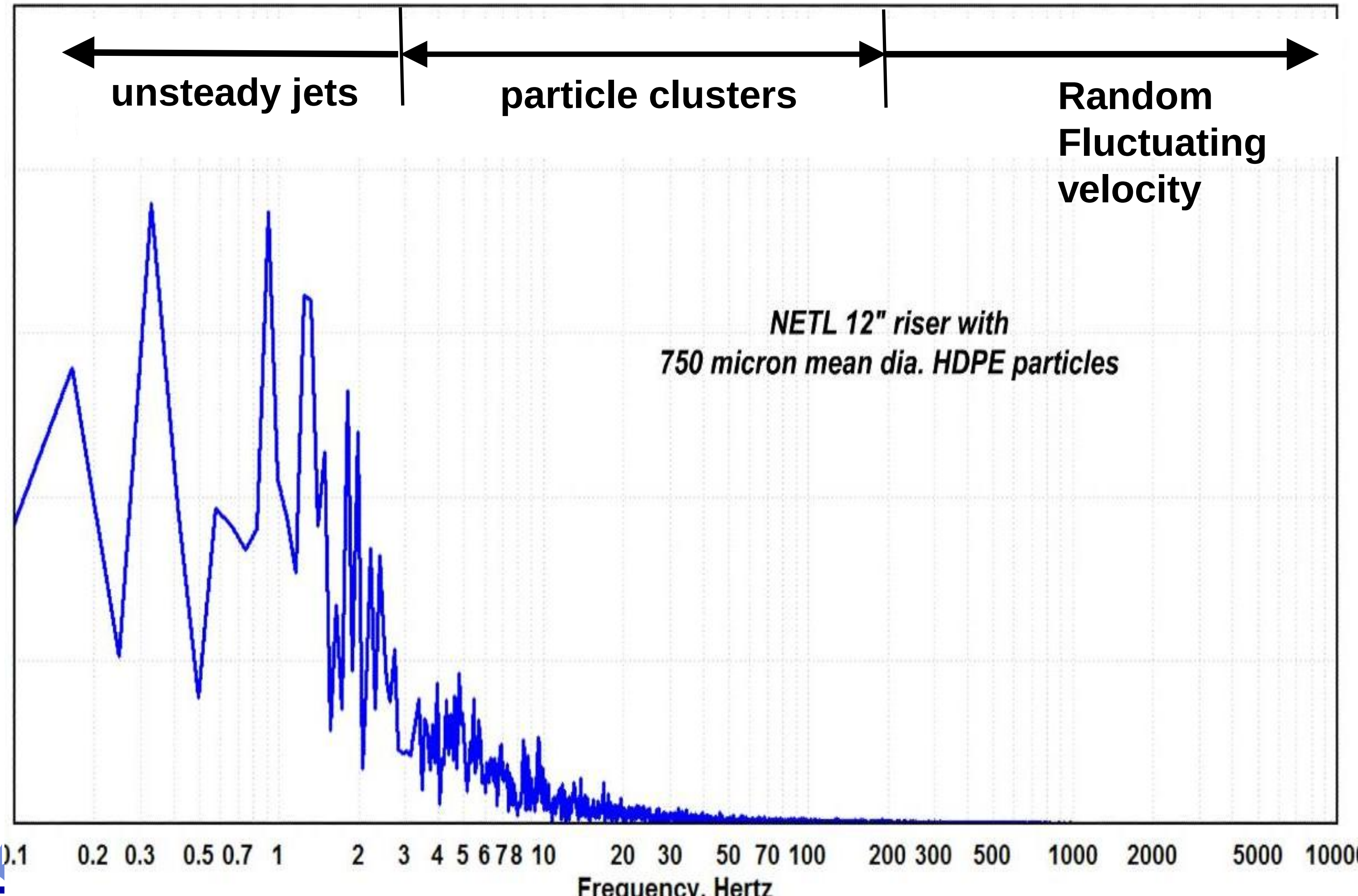
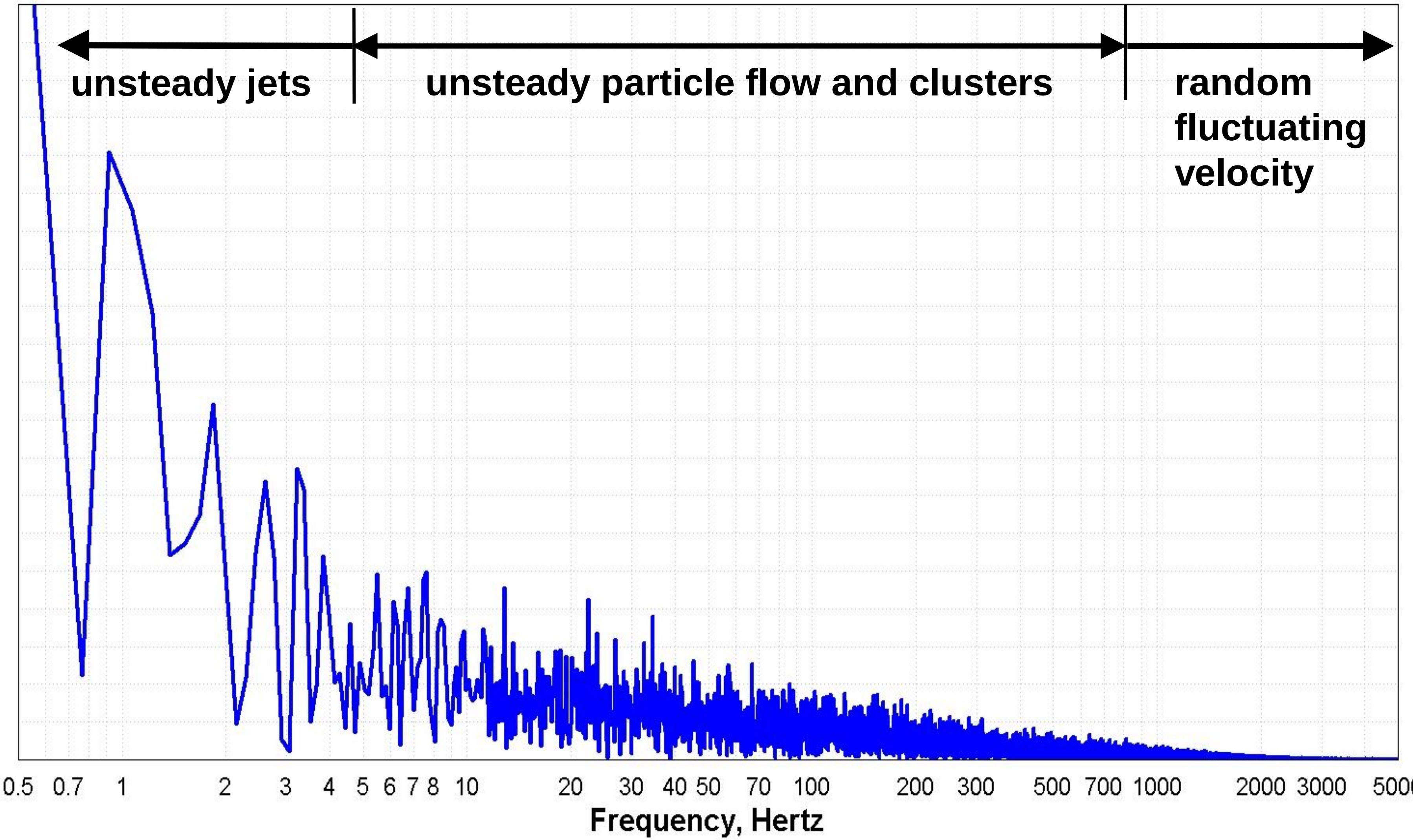
FFT of Frame Avg'd Velocity: Freq Ranges of Flow Structures
NETL 12" Riser; 750 micron mean HDPE; gas = 6.6 m/s ; solids flux = 80 kg/m2/s



FFT of Frame Avg'd Velocity: Freq Ranges of Flow Structures

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



Two Types of Particle Clustering: in/above Fluidized Beds and in Risers

Two Types of Particle Clustering: in/above Fluidized Beds and in Risers

Clusters in fluidized beds and clusters in risers have been shown to be different phenomena

Clustering in/above Fluidized Beds (< 1m/s) :

- **Small, 5-100 particles**
- **low velocities and low shear (< 1 m/s)**
- **high interparticle attraction forces**
- **particles in stay locked together for long periods**

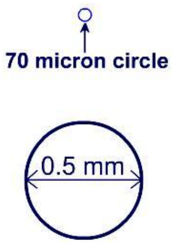
Clustering in Risers (> 5m/s):

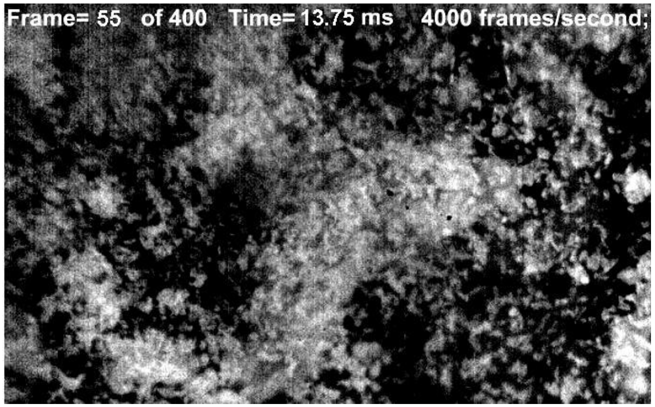
- **Large, >1000 particles**
- **High velocity, high shear (> 5 m/s)**
- **low interparticle attraction forces**
- **clusters deform and particles move relative to each other**

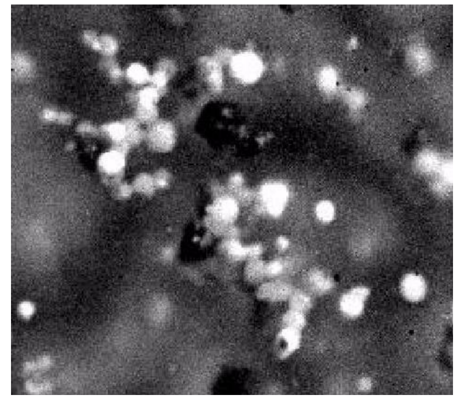
NETL

Types of Particle Clustering

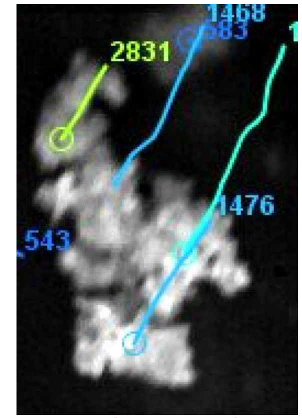
Clustering in/above Fluidized Beds (< 1m/s) :







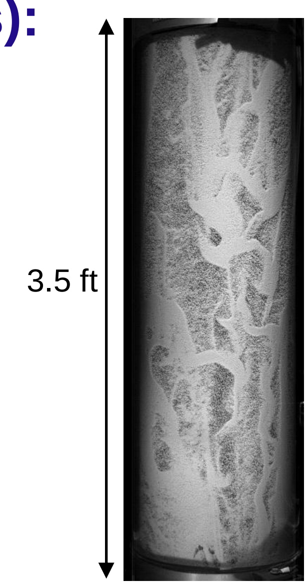
Inside a fluidized bed

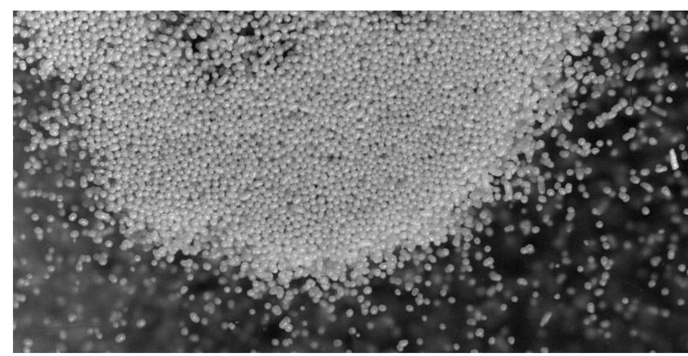


Polyethylene above a fluidized bed

Clustering in Risers (> 5m/s):

FCC in PSRI 8” riser





Clusters in NETL 12” riser

Conclusions

- **NETL developed new high speed PIV system**
- **New software developed to automatically extract particle flow data from high speed PIV videos. Patent pending.**
- **New borescope designed for particle imaging at high particle concentrations. DOE Invention Discovery filed.**

Conclusions

Unique advantages of NETL HSPIV system:

- **sample rates up to 1 million vectors per second, allowing first complete measurement of granular temperature in risers**
- **Highly accurate: measurement uncertainty < ±1%**
- **Only measurement technique that allows each data point to be reviewed in a high speed video showing particle motion**

Conclusions

Applications and Findings:

- **Cluster studies with PSRI**
  - **First visualization of clusters *inside* a fluidized bed**
  - **Size and velocity distribution measured in-situ above a fluidized bed**
  - **Clusters in fluidized beds and clusters in risers are different phenomena**

- **Riser flow behavior shown to be unsteady jets rather than core-annulus**

- **First complete granular temperature data**

Thank You

- This work was made possible by working in a National Laboratory
- Thanks to PSRI for their lab (and for being fun to work with)
- Special thanks to Bill Rogers, Larry Shadle, Chris Guenther and Madhava Syamlal for funding this work
- Most special thanks to my wife for tolerating my long hours while developing this technology
- Thank you for staying for the afternoon of the last day of the conference

Particle Image Recognition Step of HSPIV

- The following slides are supplied as additional material describing the particle image recognition step of HSPIV.
- A robust algorithm is provided that does a good job recognizing particle images for a range of different particle types.
- For more information, contact Franklin Shaffer at

Franklin.Shaffer@netl.doe.gov

412-386-5964

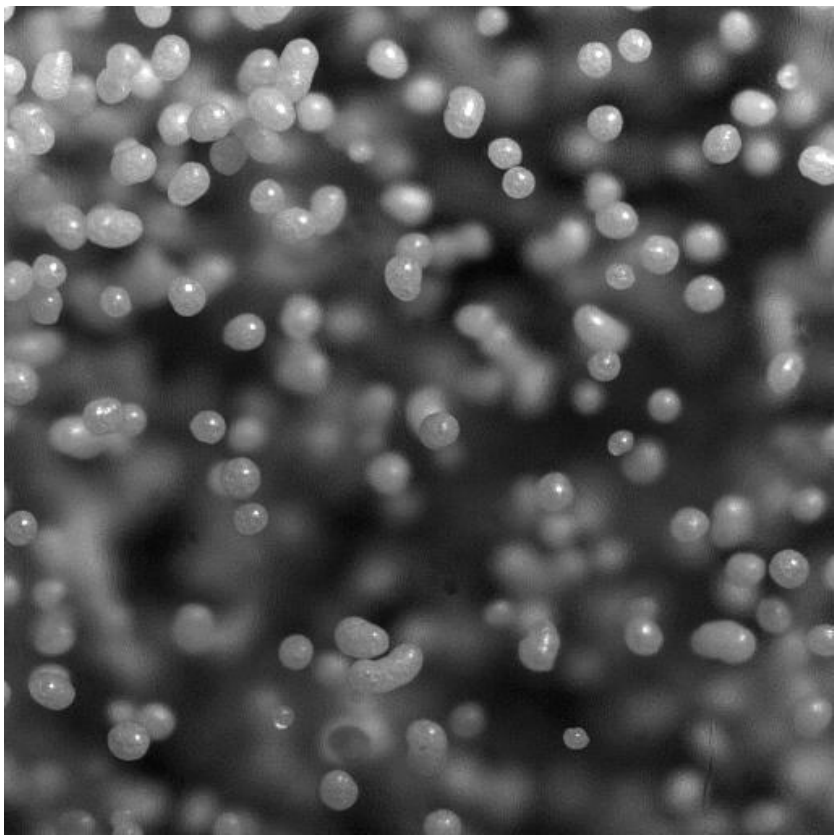
Particle Image Recognition Step of HSPIV

- **Objective is to recognize particle images, then find geometric centers of particle images (centroids)**
- **Mathematically, this is a problem of finding maxima in a field with noise and variation in background level**
- **Particle Image Recognition is a mature technology: many off-the-shelf software packages available (ImageJ, Matlab, Image Pro, etc.)**

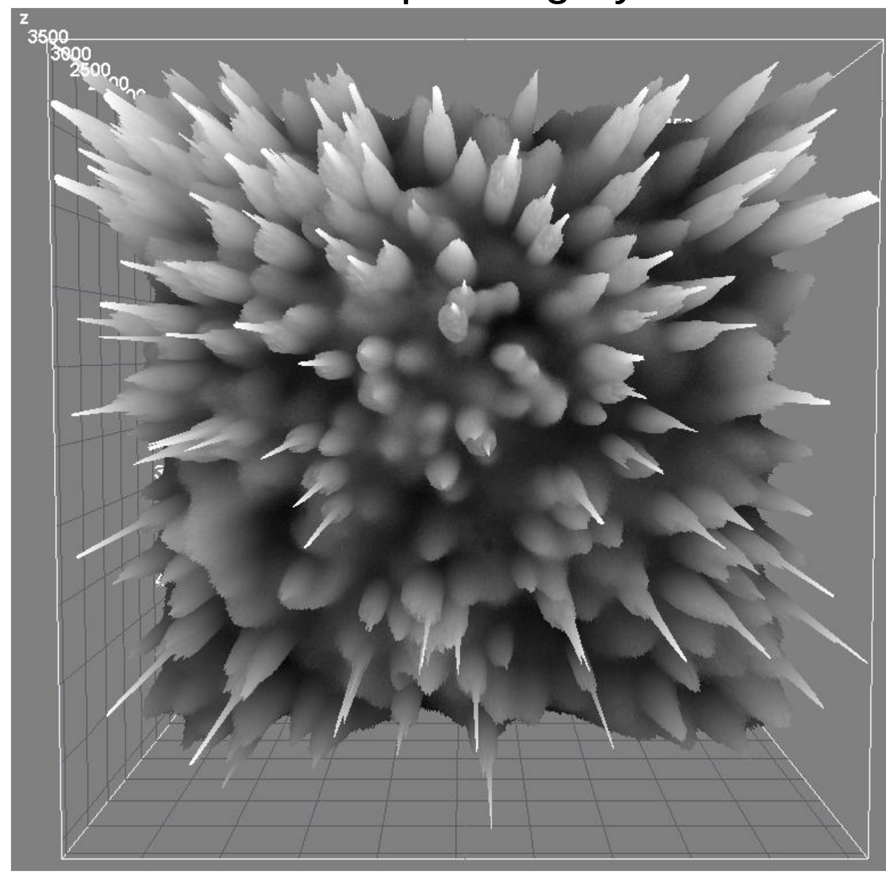
Particle Image Recognition Step of HSPIV

Standard problem of finding maxima in a noisy, varying background

Example image: JP123 frame 1083



3D surface plot of grey level



Particle Image Recognition Step of HSPIV

- “Specular” bright spots were created intentionally using a small light source near the camera. Bright spots are a reflection of the light source.
- Bright spot technique only works for very large, reflective, spherical particles like HDPE. Does not work for glass beads, FCC, sand, etc.
- We use NIH’s ImageJ. Built in particle analysis tools are more than adequate.
- We have gross oversampling, so if we recognize >50% of in-focus particles, the velocity signal is completely resolved.
- **Only area possibly needing more research in particle image recognition is defining depth-of-field. Depth-of-field used to convert number concentration to solids fraction.**

Particle Image Recognition Step of HSPIV

- **We use NIH's ImageJ**
  - widest range of built-in tools for particle image analysis (by far).
  - Developed for image analysis of biological cells, which closely resemble particle images
  - Free
  - Connection to community of researchers using ImageJ

- **We have gross oversampling, so if we recognize 80% of in-focus particles, we're happy. ImageJ's built-in tools are more than adequate.**

- **<u>Only area possibly needing more research in particle image recognition is defining depth-of-focus.</u>**
- **Depth-of-focus is needed for calculation of absolute particle concentration (solids fraction).**

Relative Particle Concentration

- **The thickness (depth-of-field) in HSPIV measurements is dependent on entire optical system *and* particle image recognition techniques**
- **In this field, “solids fraction” is often calculated by assuming a value for depth-of-field**

$$solids\_fraction = \frac{no\_particles\_in\_a\_frame}{(field-of-view\_area)\times depth\_of\_field}$$

- **measurement uncertainty is high and a linear relationship is assumed between number particles detected and solids fraction**
- **So we use instead the Relative Particle Concentration (RPC)**

$$\textit{Relative Particle Conc} = \frac{no\_particles\_in\_a\_frame}{\max imum\_number\_of\_particles\_in\_any\_frame}$$