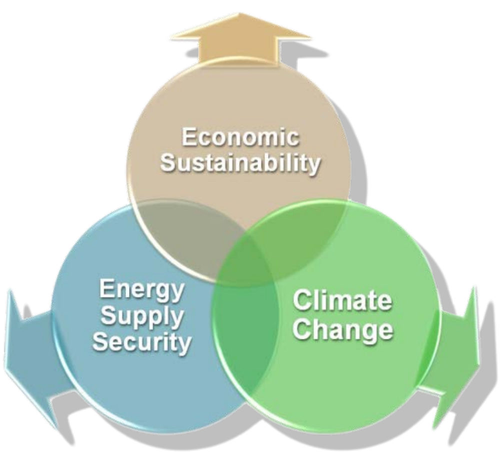
NATIONAL ENERGY TECHNOLOGY LABORATORY

Development of a Microwave Sensor for Measurement of Solids Mass Flow in Chemical Looping



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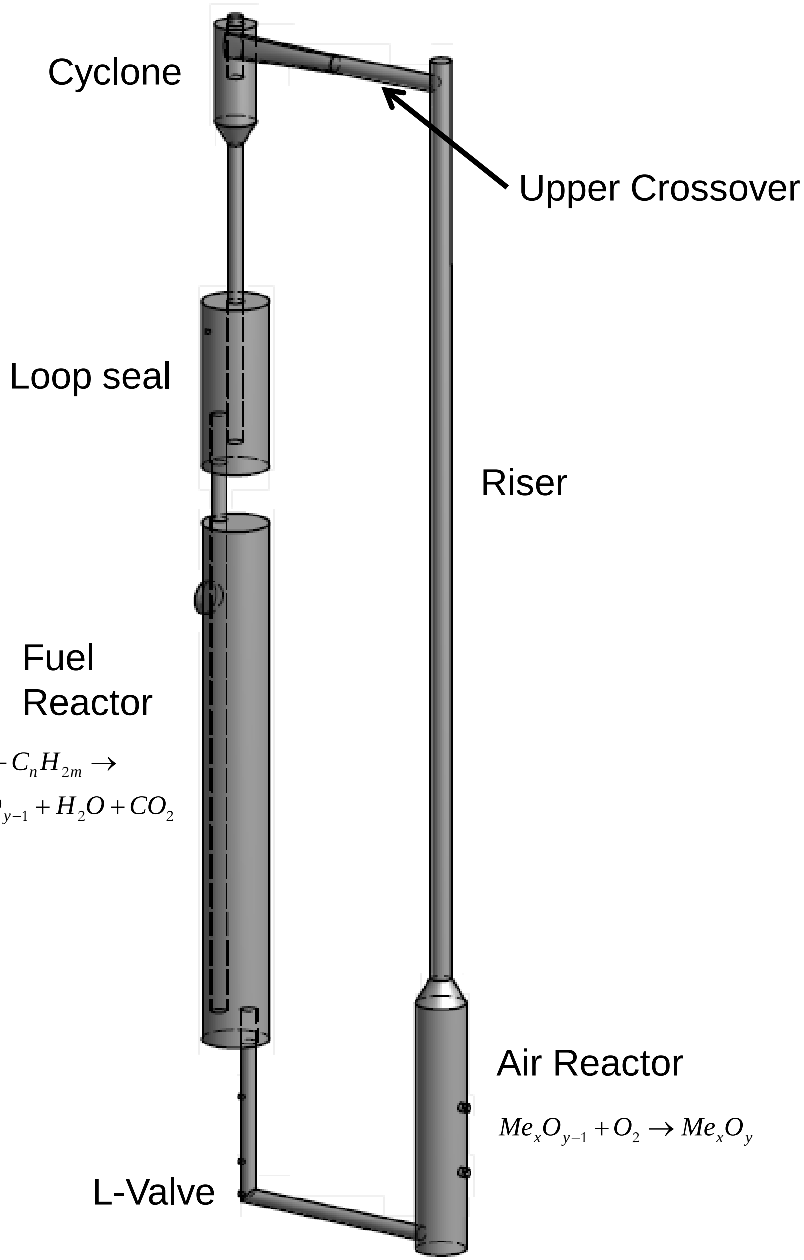
National Energy Technology Laboratory

U.S. DEPARTMENT OF ENERGY

Chemical looping combustion system

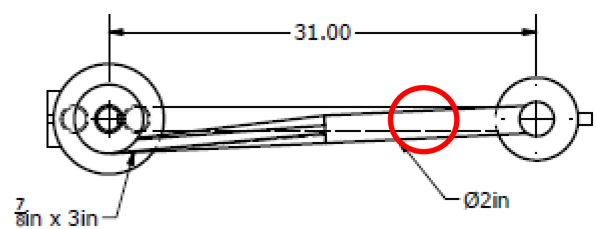


$$Me_xO_y + C_nH_{2m} \rightarrow Me_xO_{y-1} + H_2O + CO_2$$

$$Me_xO_{y-1} + O_2 \rightarrow Me_xO_y$$

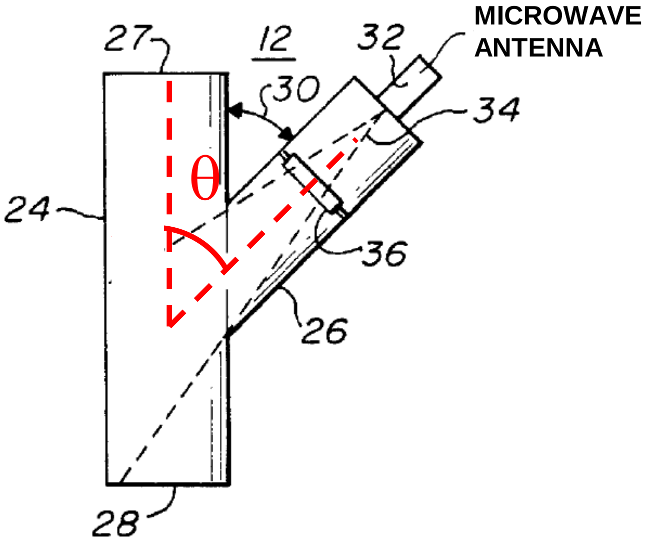
- Metal oxide particles transport oxygen from the air reactor to the fuel reactor
- The mass flow rate of the oxygen carrier particles is an important process parameter
- *Microwave Doppler sensing* has been selected as the measurement technique

Top view of Upper Crossover Flowpath

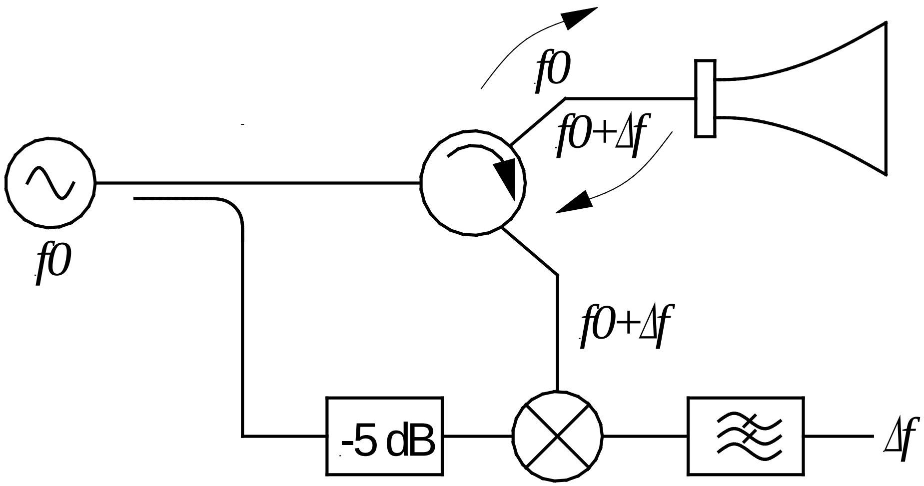


Microwave Doppler sensing

Sensor configuration



Electronic schematic



$$\Delta f = 2f\frac{v}{c}\cos\theta$$

$$P_{reflected} = N\sigma_{total\ scattering}P(x)dx$$

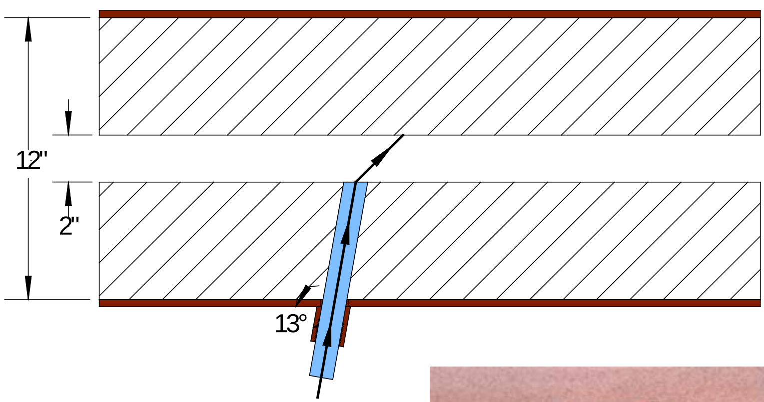
$$mass\ \ flow\ rate = \rho \cdot v \cdot A$$

$$\sim \Delta f \cdot P_{reflected}$$

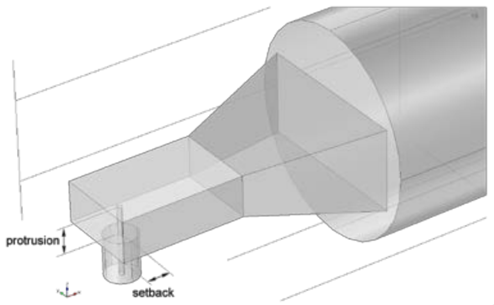
Microwave Doppler for chemical looping

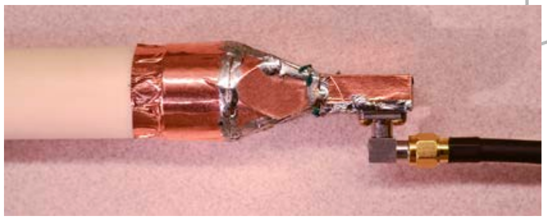
- High temperature (~1000 C) and high pressure (~10 atm)
- Circular alumina waveguide to inject microwaves
- Custom coaxial/ circular waveguide transition

launcher attached to reactor

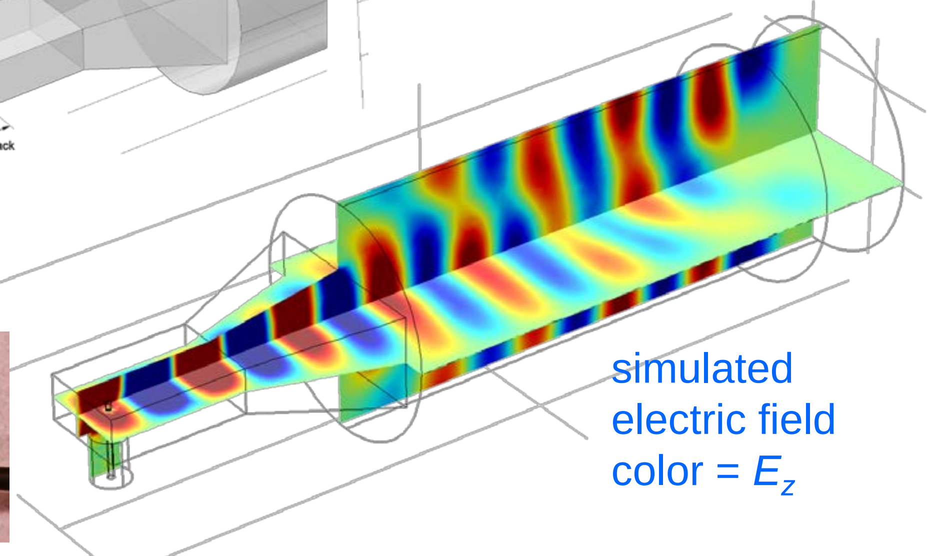


coax to circular transition





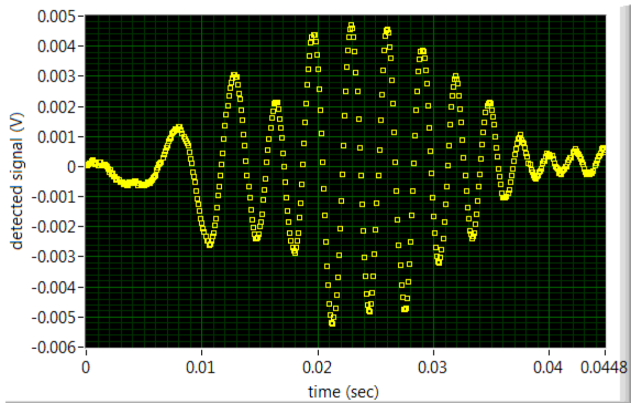
prototype launcher

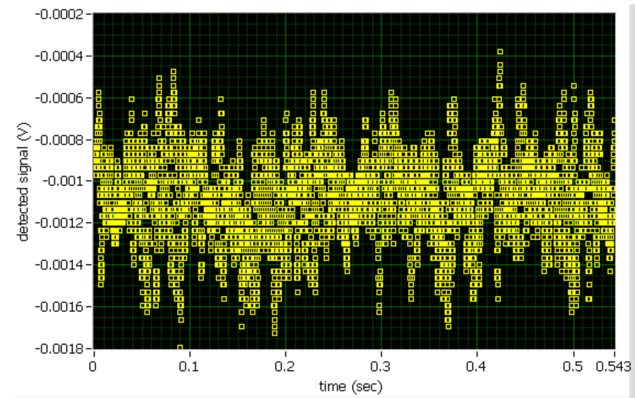


simulated electric field color = E_z

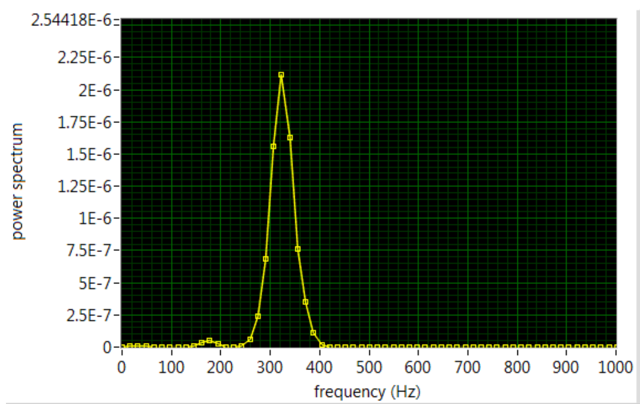
Single particle *vs.* many particles

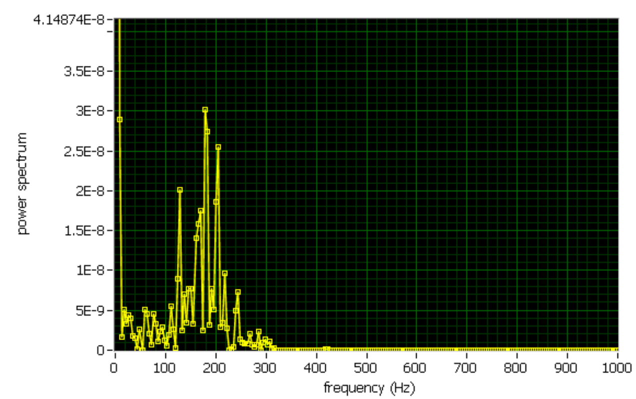
mixer output





Fourier power spectrum



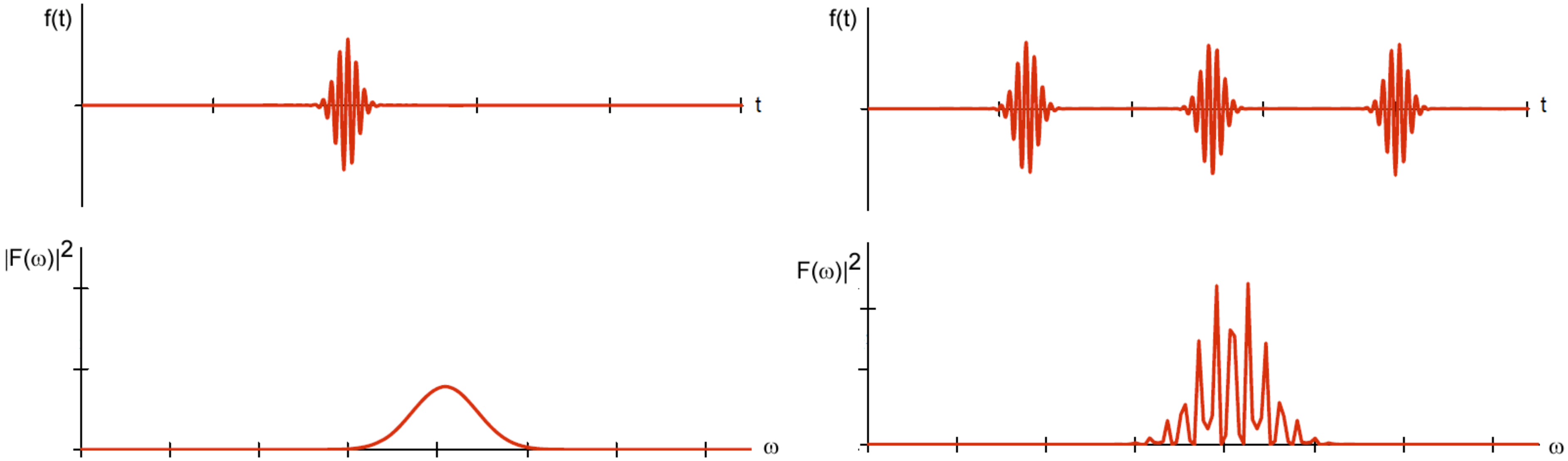


steel ball 0.157" diameter falling 1.8 m, horn angle 42 degrees; 10 GHz

150 μm diameter ilmenite particles falling 2.1 m, horn angle 52 degrees; 10 GHz

A numerical experiment

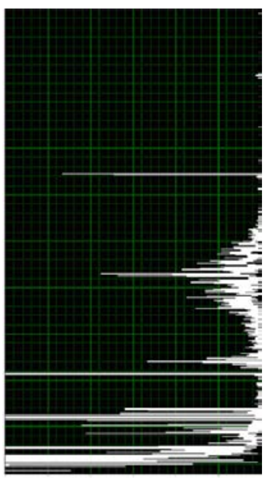
Compare FFT of signal from a single scatterer with FFT of signal from multiple scatterers

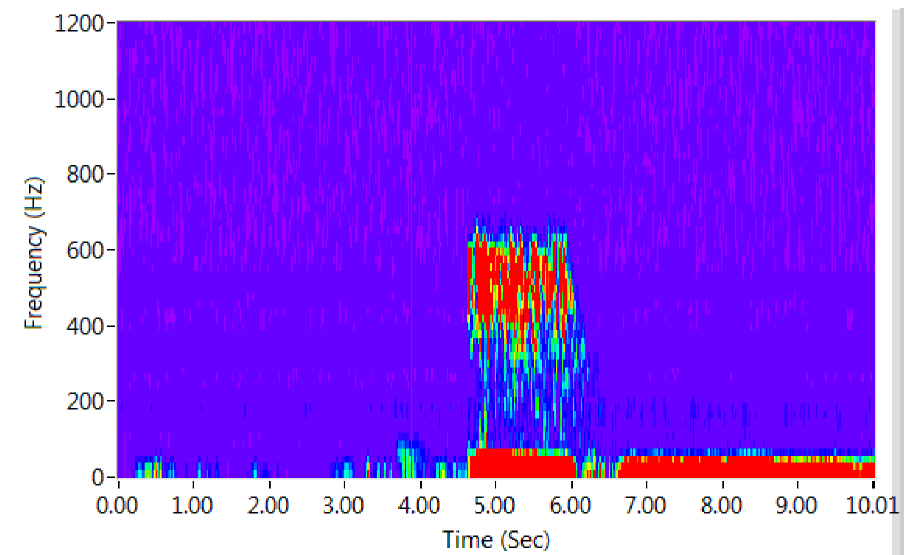


The envelope (frequency shift) remains indicative of strength of scattering (velocity)

JTFA suggests an approach for analysis

- Joint time-frequency analysis
  - perform FFT of a chunk of data
  - plot FFT (intensity color-coded) along *y* axis
  - plot for each chunk along *t* axis



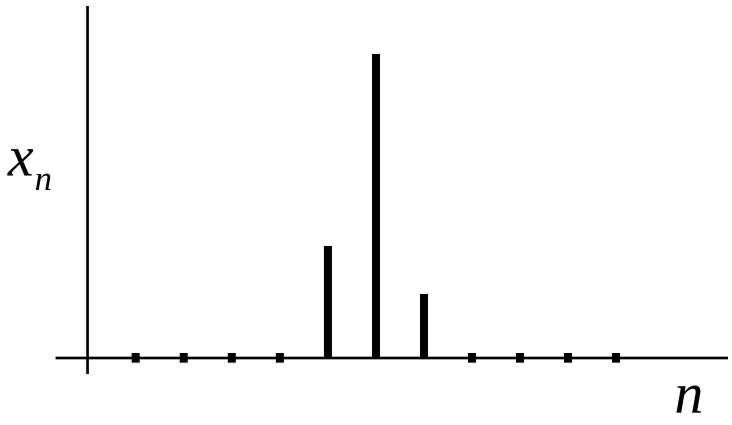


integrated strength of scattering is related to mass density

centroid is related to average velocity

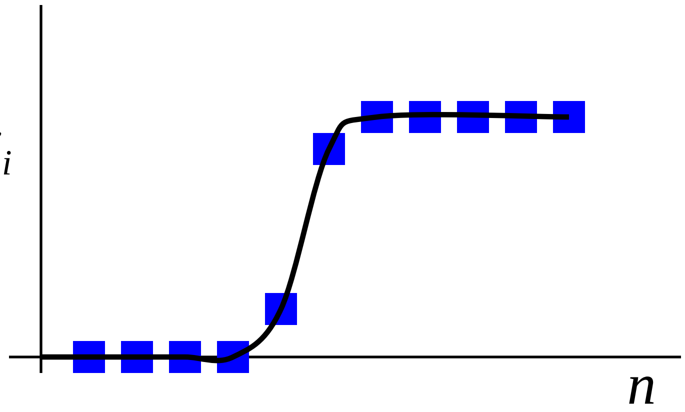
128 gm total flow, 24 GHz

Cumulative distribution function



distribution (FFT of acquired data)

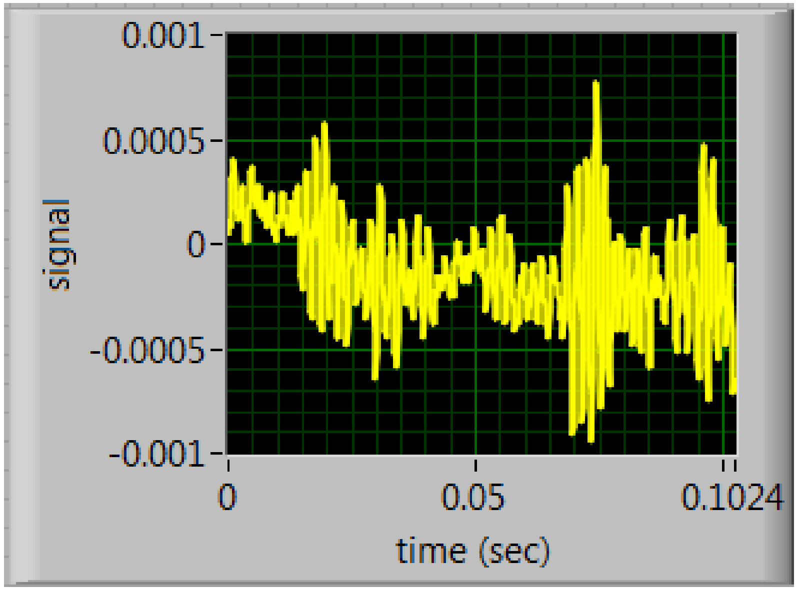
$$CDF_n = \sum_{i=1}^{n} x_i$$



cumulative distribution function

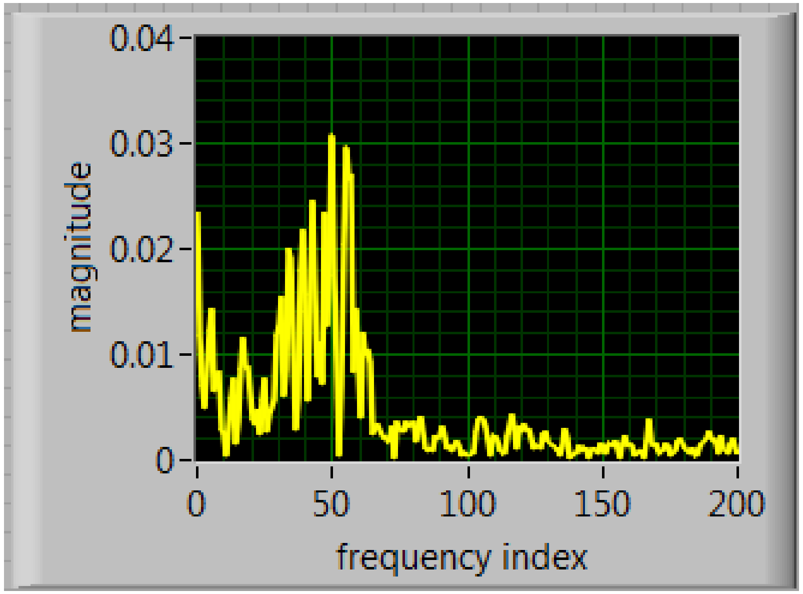
Data analysis steps

1. select and window $n_{samples}$ (power of 2)



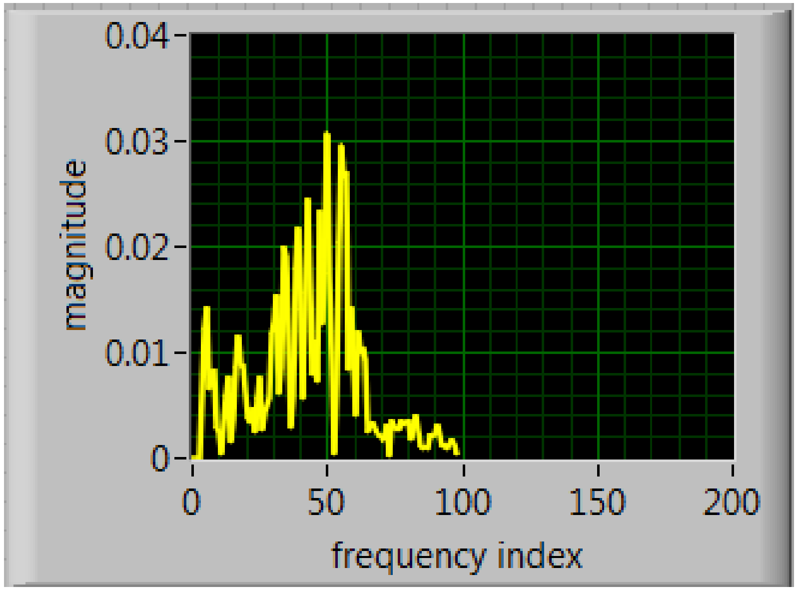
Data analysis steps

1. select and window $n_{samples}$ (power of 2)
2. perform FFT and compute magnitude



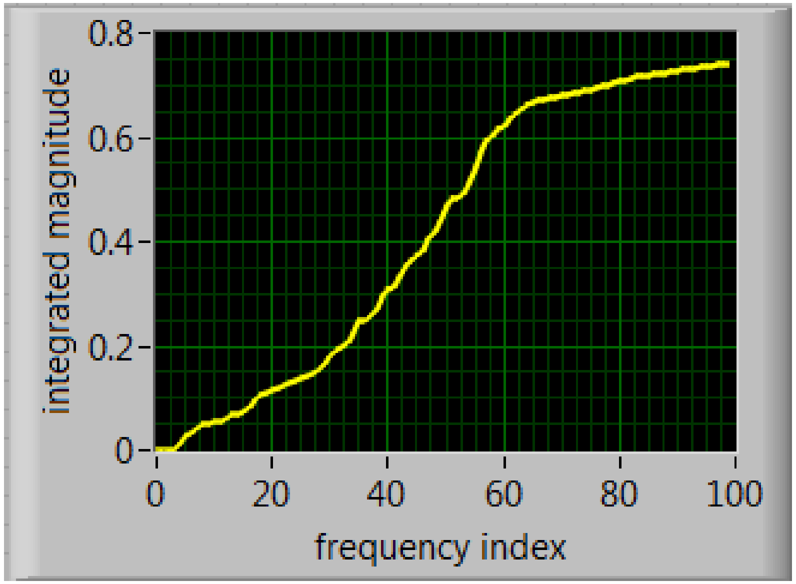
Data analysis steps

1. select and window $n_{samples}$ (power of 2)
2. perform FFT and compute magnitude
3. pad low frequency and crop high frequency



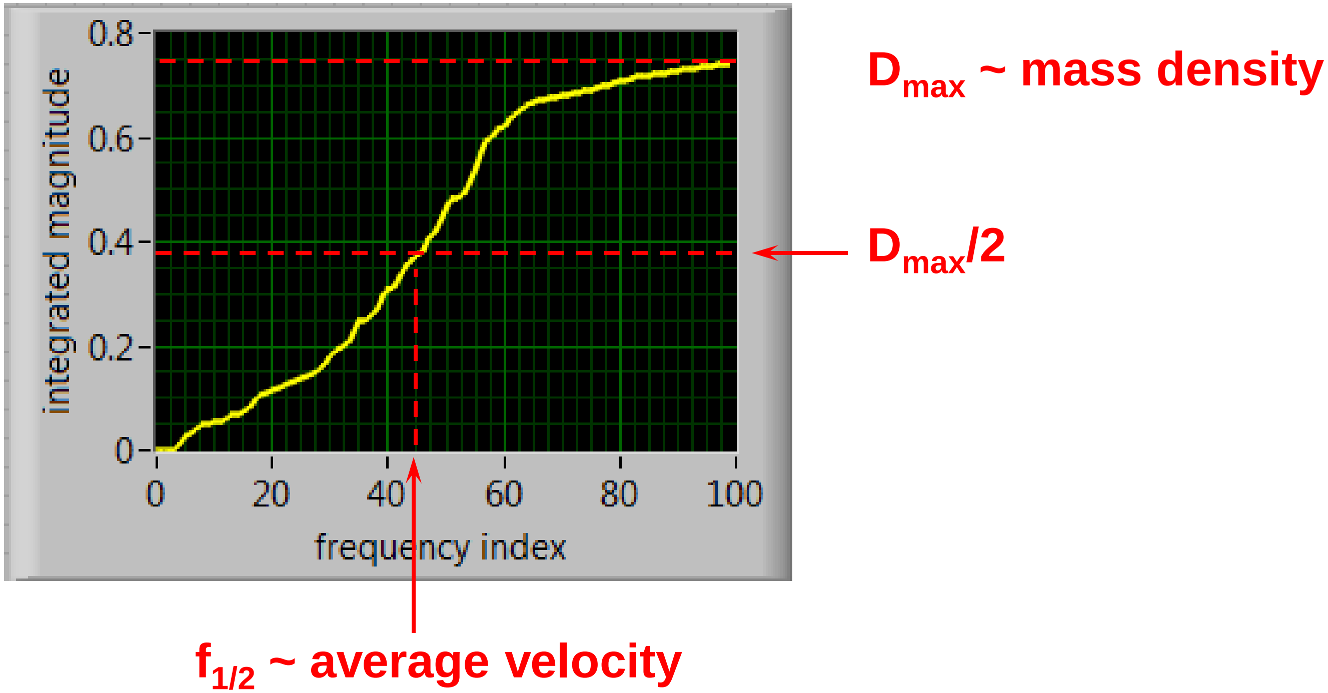
Data analysis steps

1. select and window $n_{samples}$ (power of 2)
2. perform FFT and compute magnitude
3. pad low frequency and crop high frequency
4. form cumulative distribution function



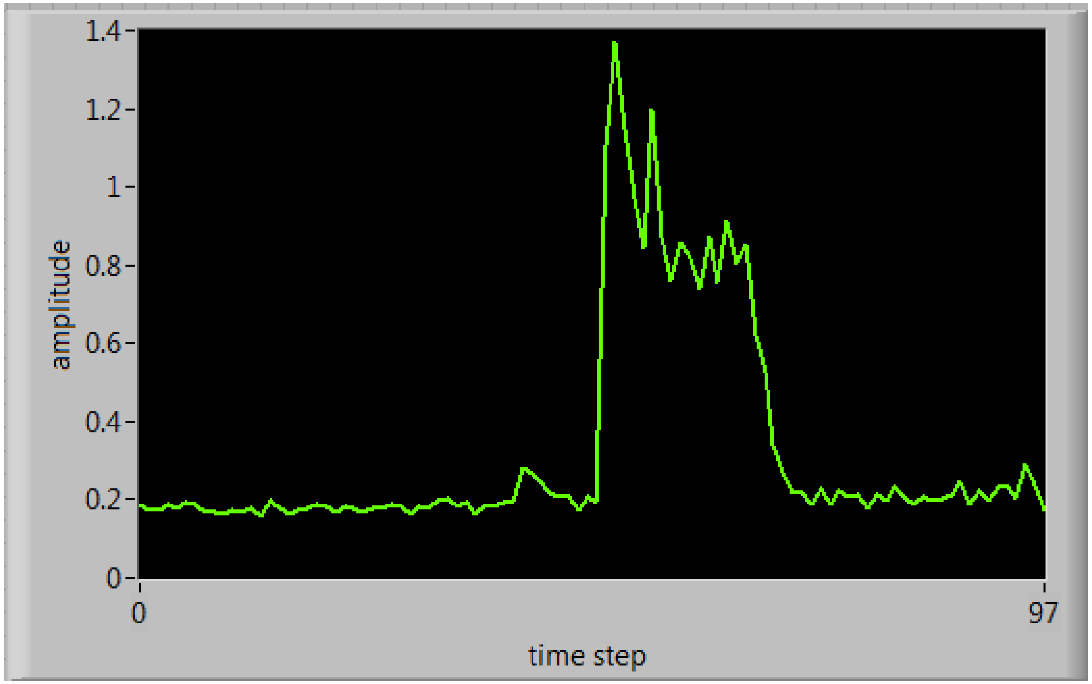
Data analysis steps

1. select and window $n_{samples}$ (power of 2)
2. perform FFT and compute magnitude
3. pad low frequency and crop high frequency
4. form cumulative distribution function
5. extract frequency shift and signal magnitude



Data analysis results

maximum of the cumulative distribution function D_{max} measures the mass density



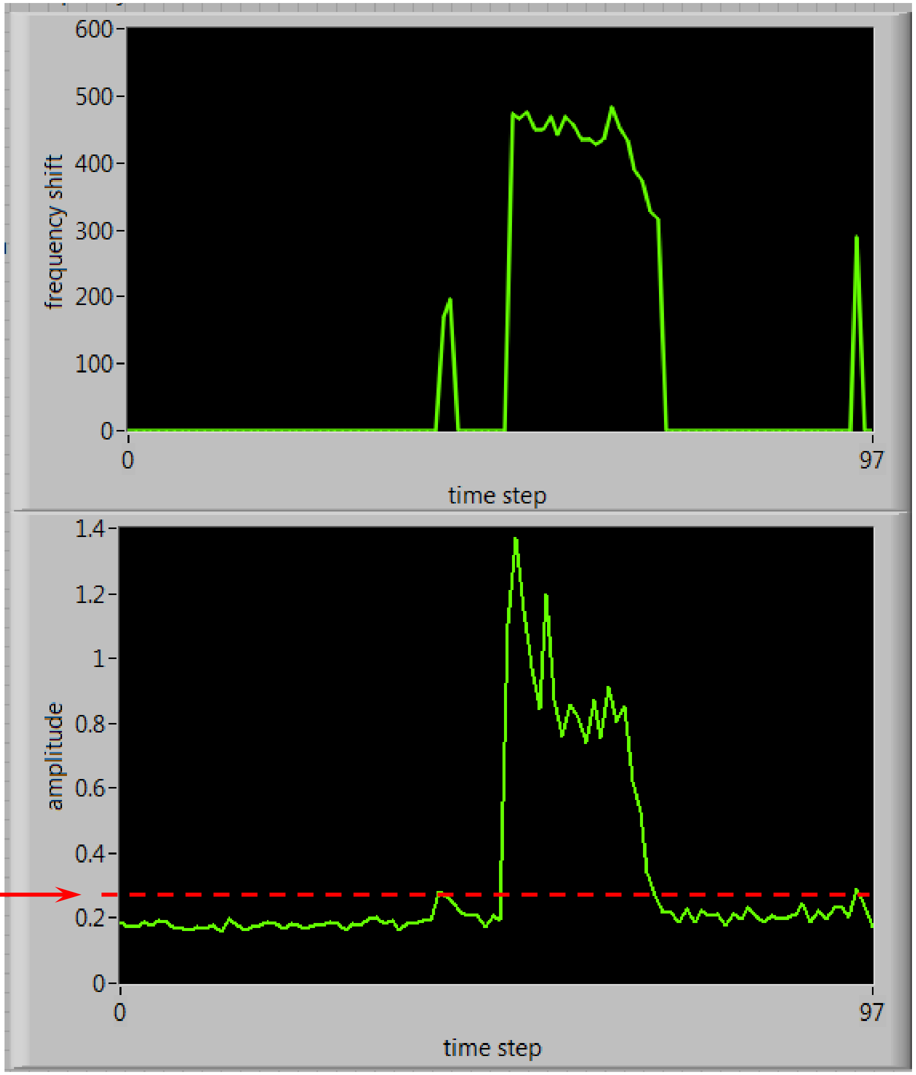
Data analysis- a fine point

$f_{1/2}$ measures the average velocity (when D_{max} is above threshold)

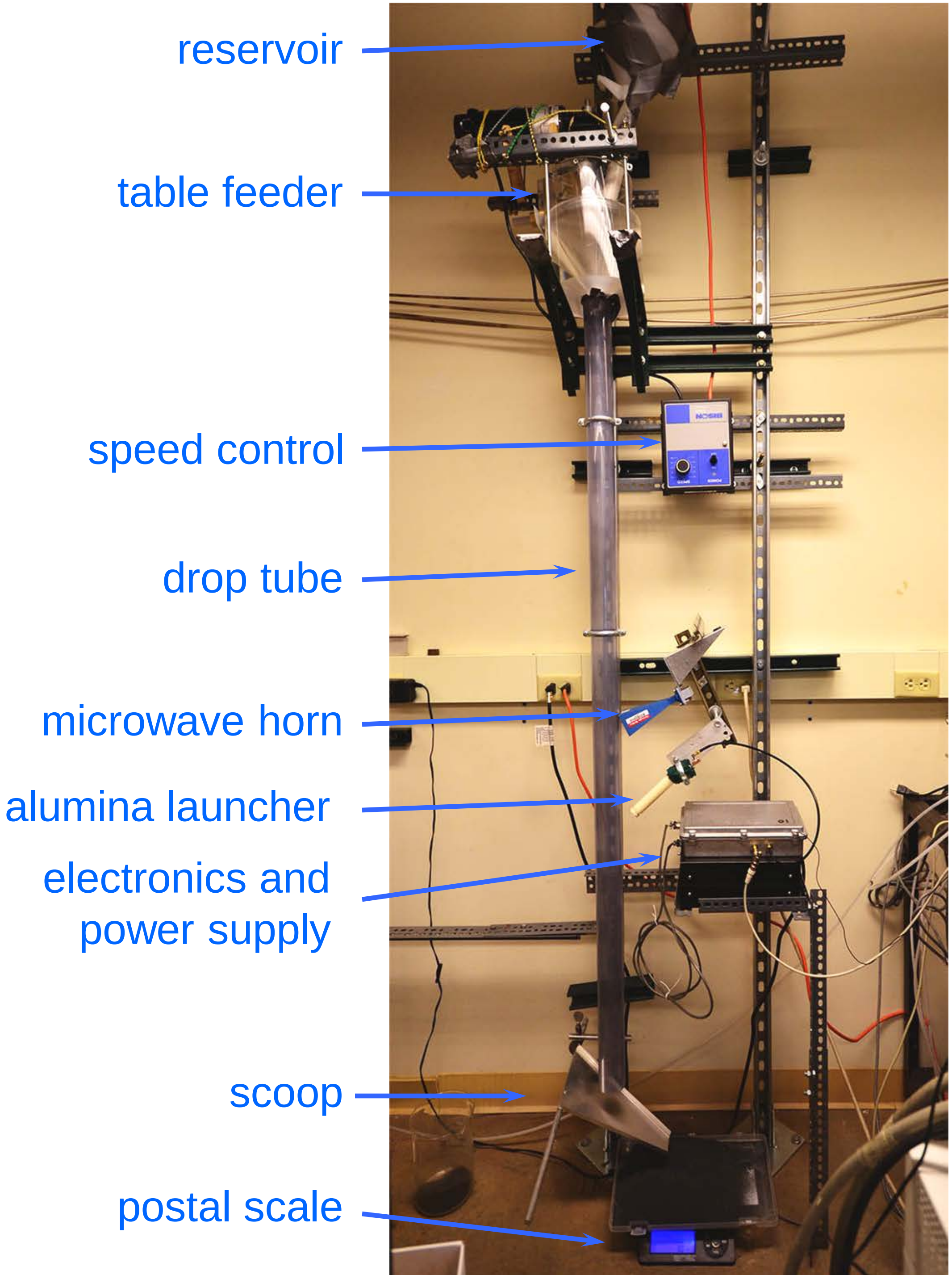
$f_{1/2} \cdot D_{max}^2$ is a measure of mass flow rate*

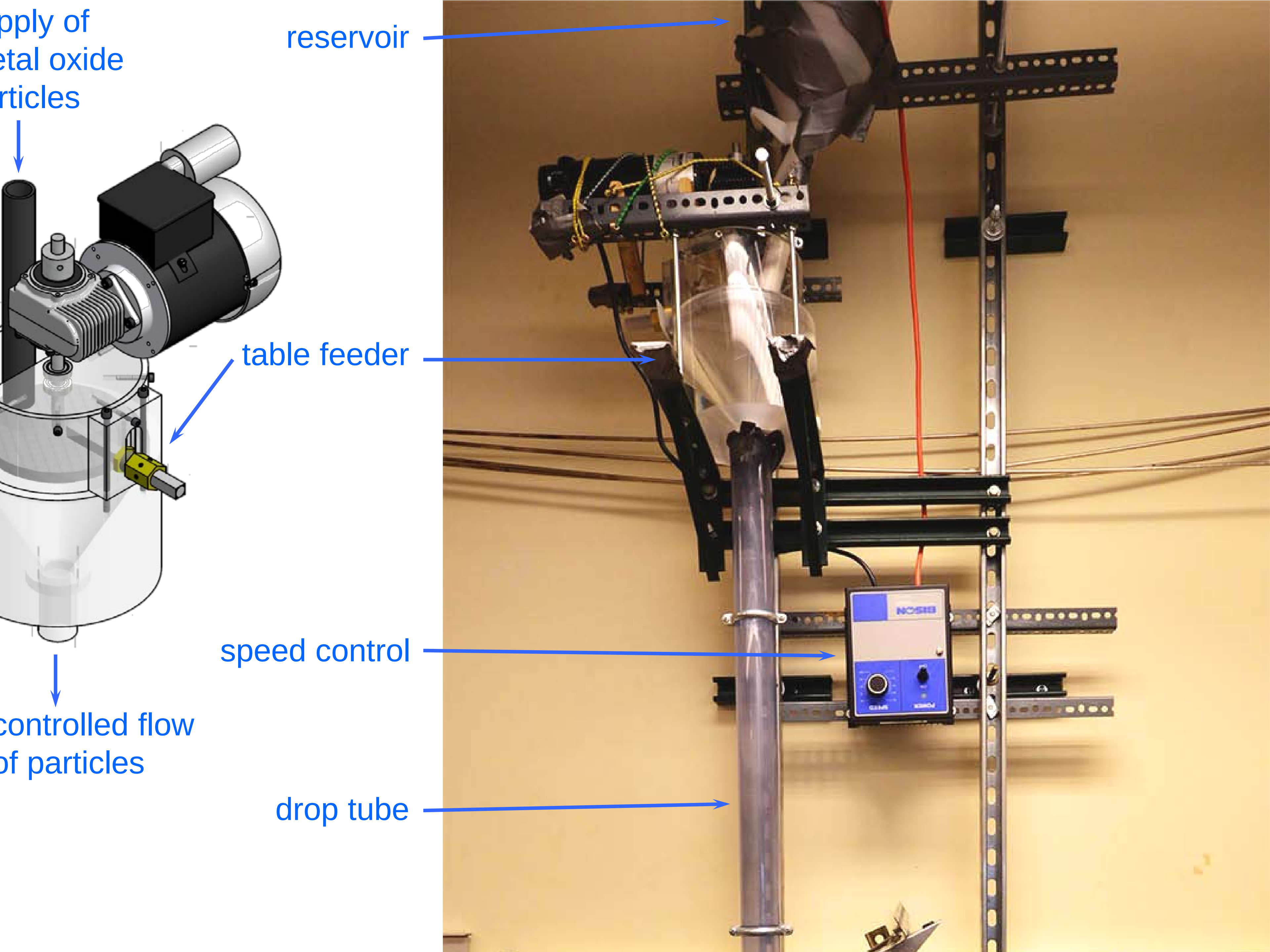
* based on theory of scattering. Not yet justified by theoretical analysis of scattering from many particles.

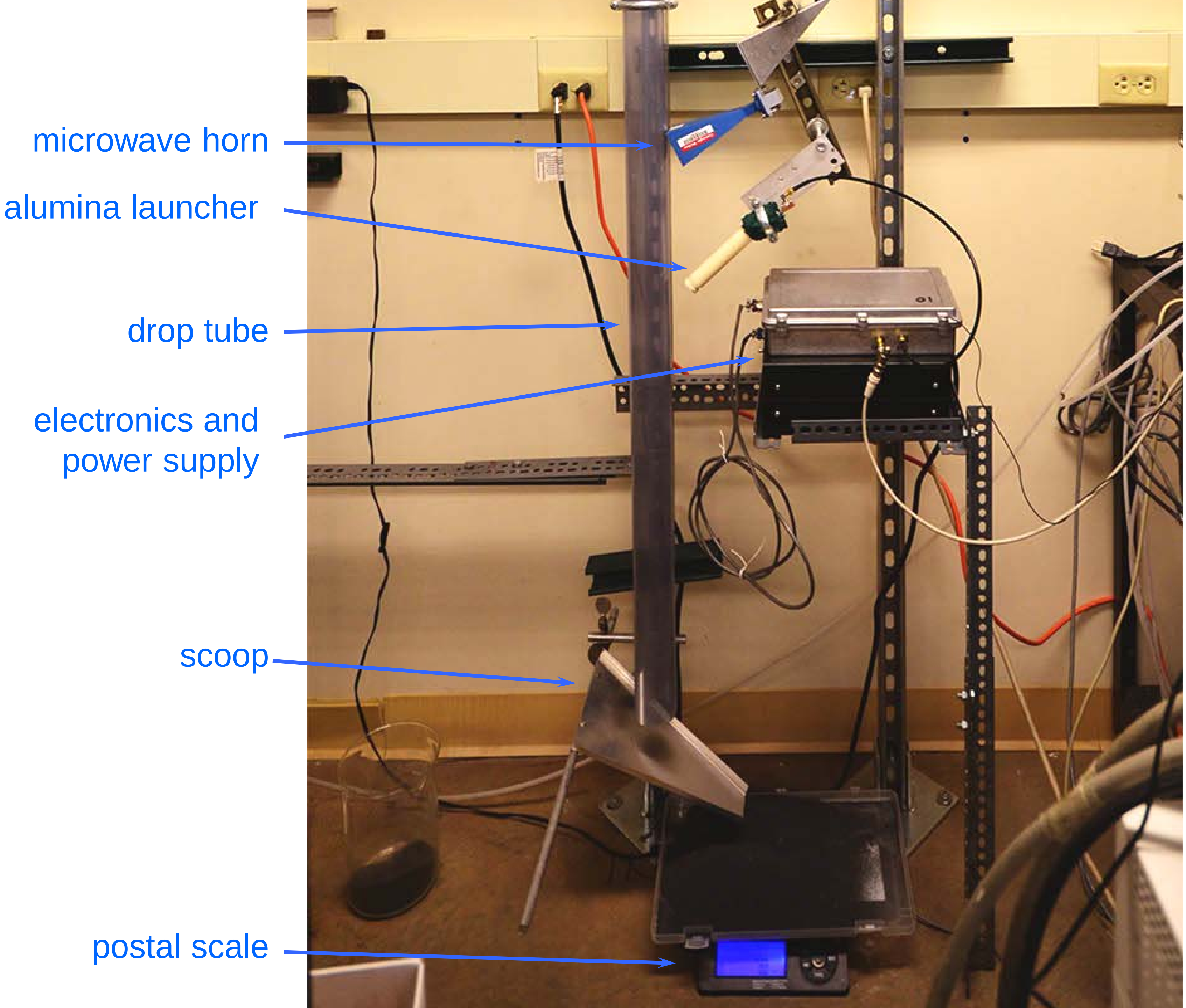
set frequency shift to zero when signal is below this level



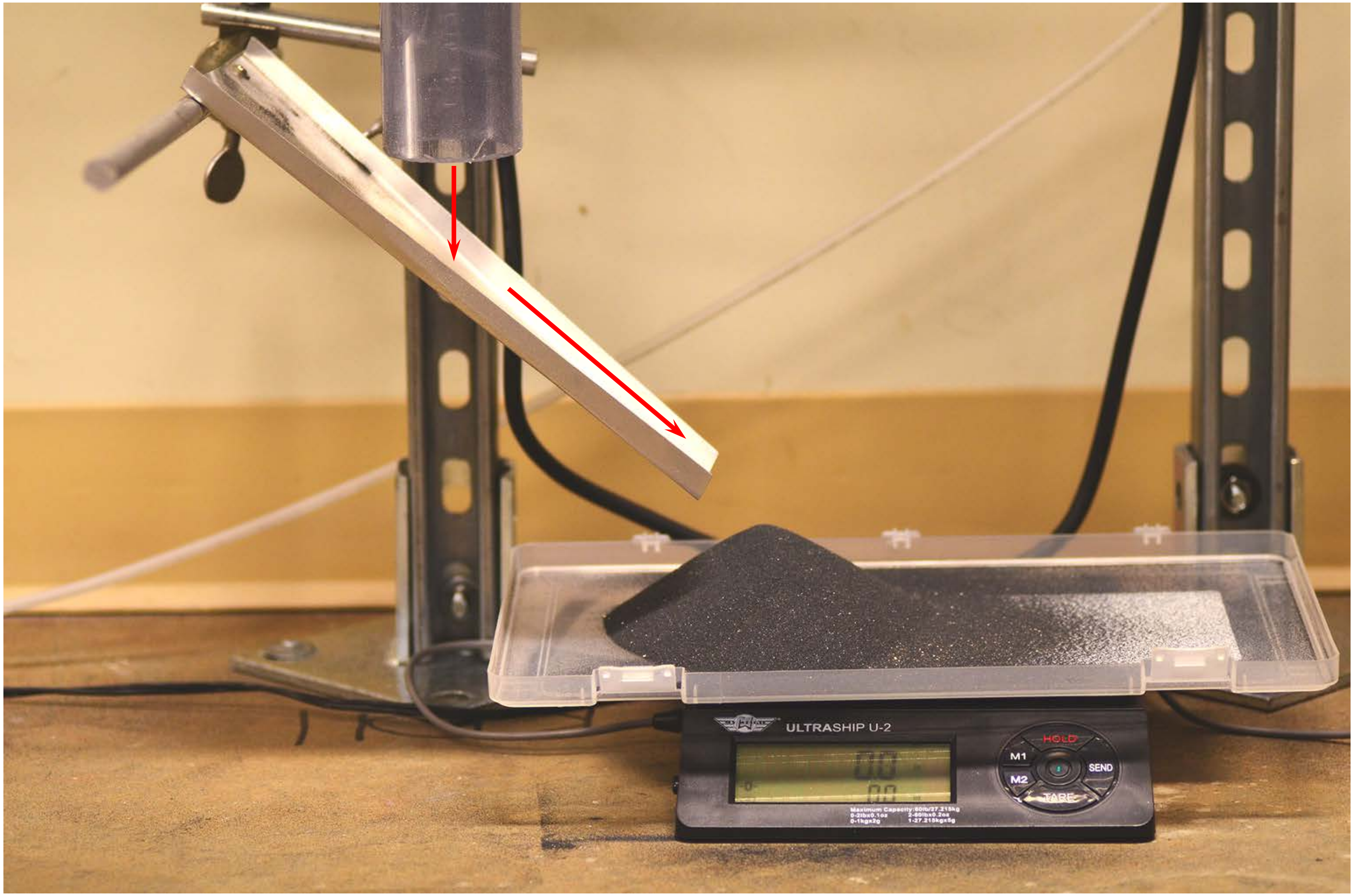
Doppler system testing



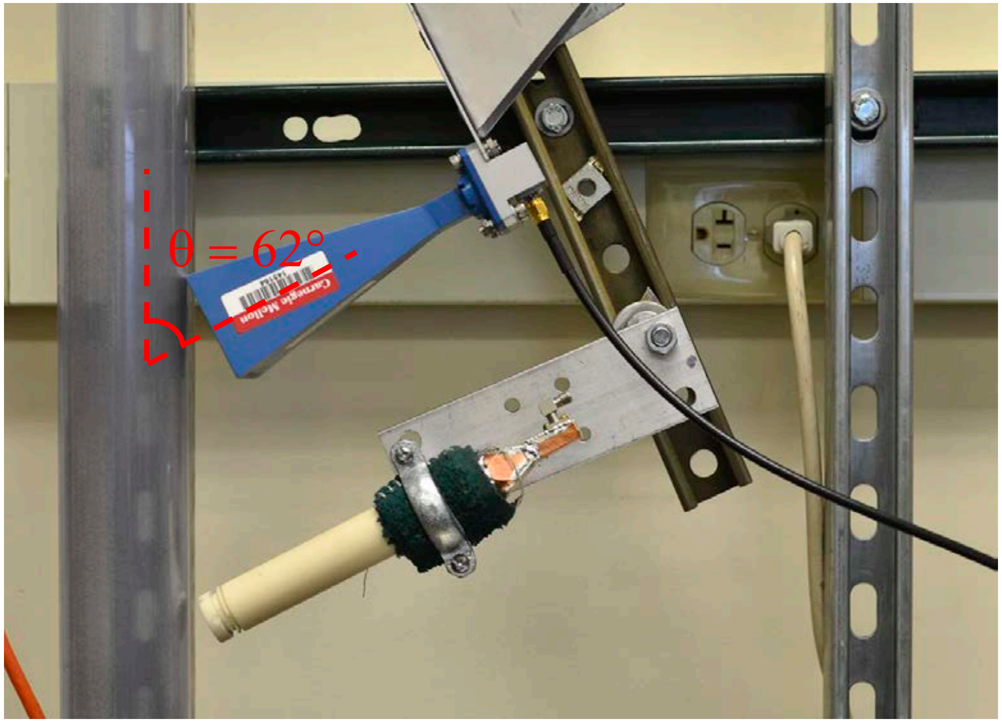

pply of
etal oxide
rticles
reservoir
table feeder
speed control
controlled flow
of particles
drop tube


microwave horn
alumina launcher
drop tube
electronics and
power supply
scoop
postal scale

Measuring mass

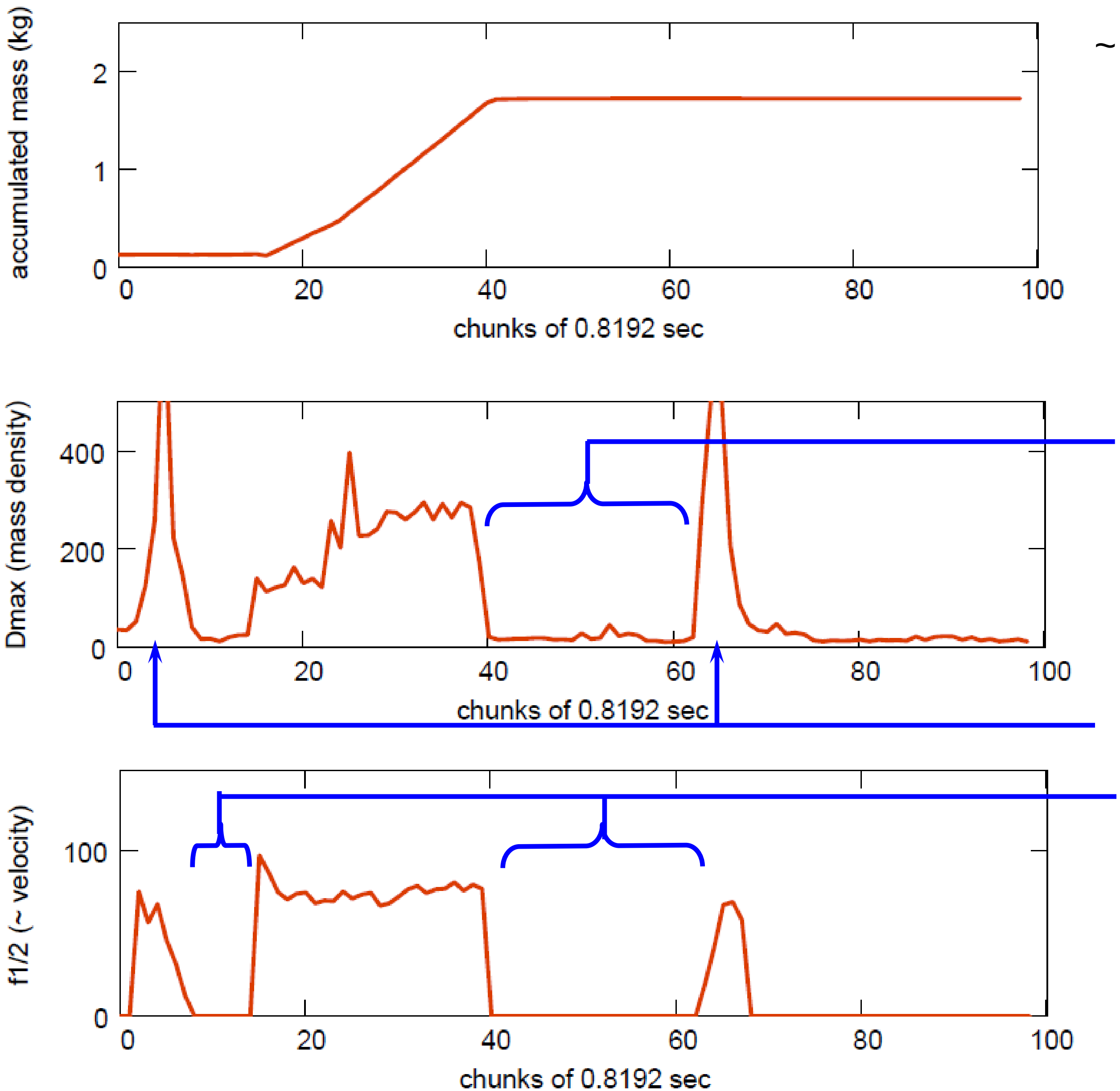


Some measurements



- ilmenite, ~ 150 μm dia.
- varying motor speed
- 10 GHz
- 8192 points/ chunk
- 10000 samples/sec

- data processed and plotted in real time, samples stored after processing

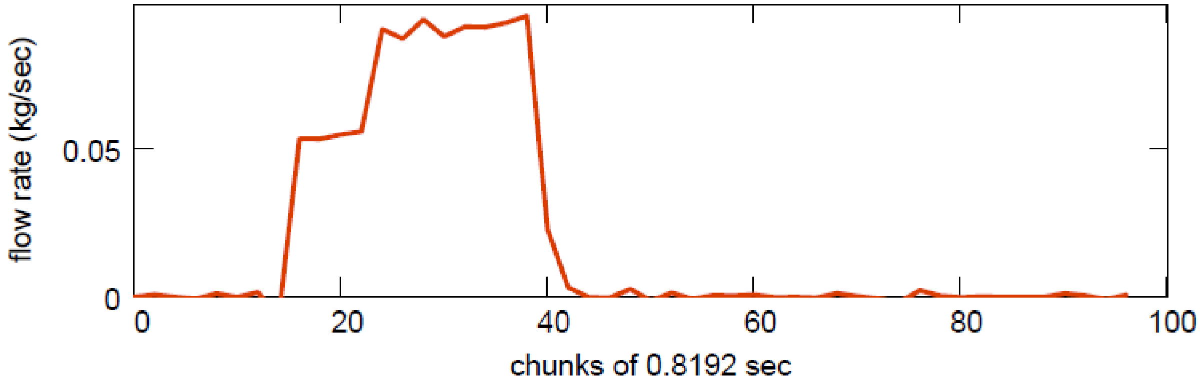


~ 25 sec flow with step change

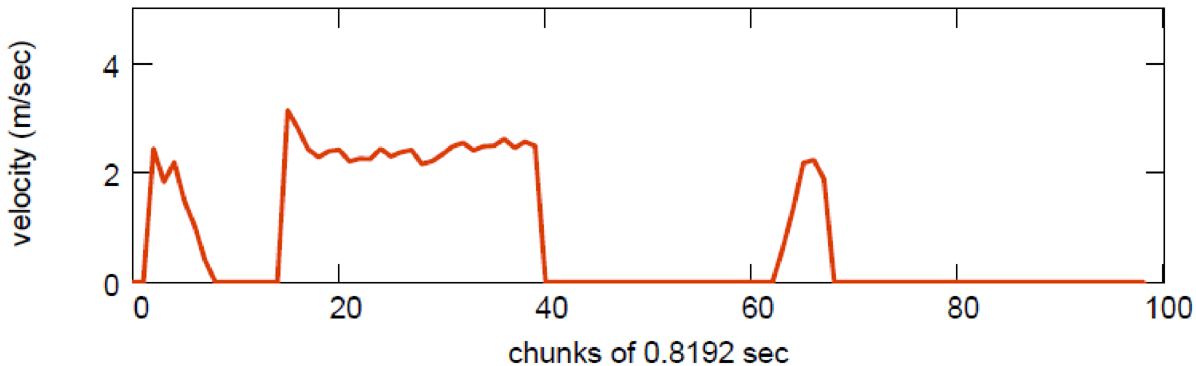
vibration from table feeder motor?

ascend/ descend ladder

$f_{1/2}$ is set to zero because D_{max} is below threshold

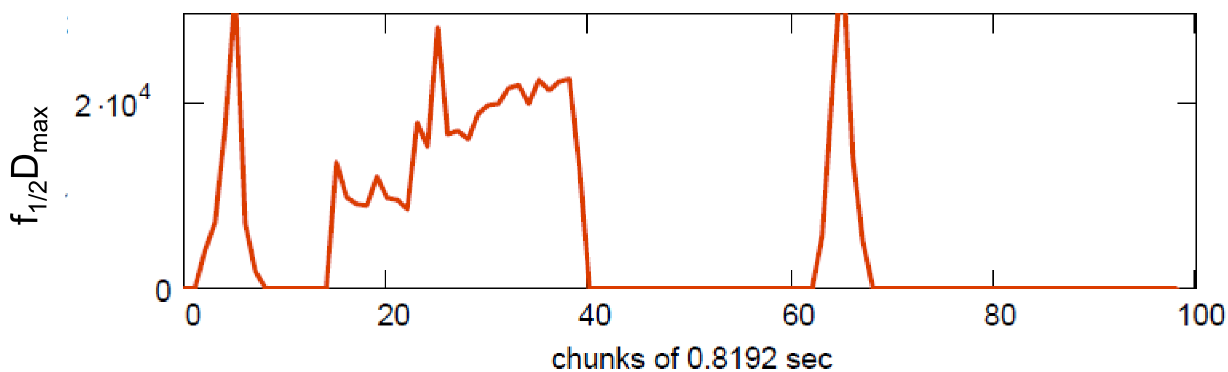


mass flow rate measured from scale



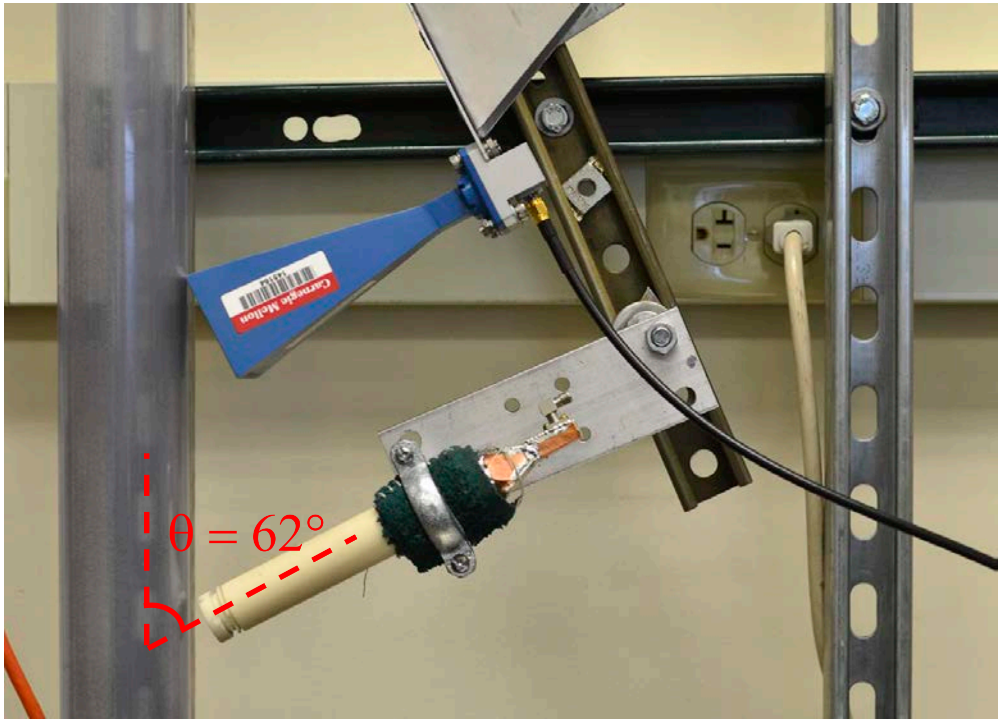
$f_{1/2}$ converted to velocity

free fall velocity = 4.7 m/sec



$f_{1/2}D_{max}^2$ seems to give mass flow that is too high- but measurements over a wider range are needed

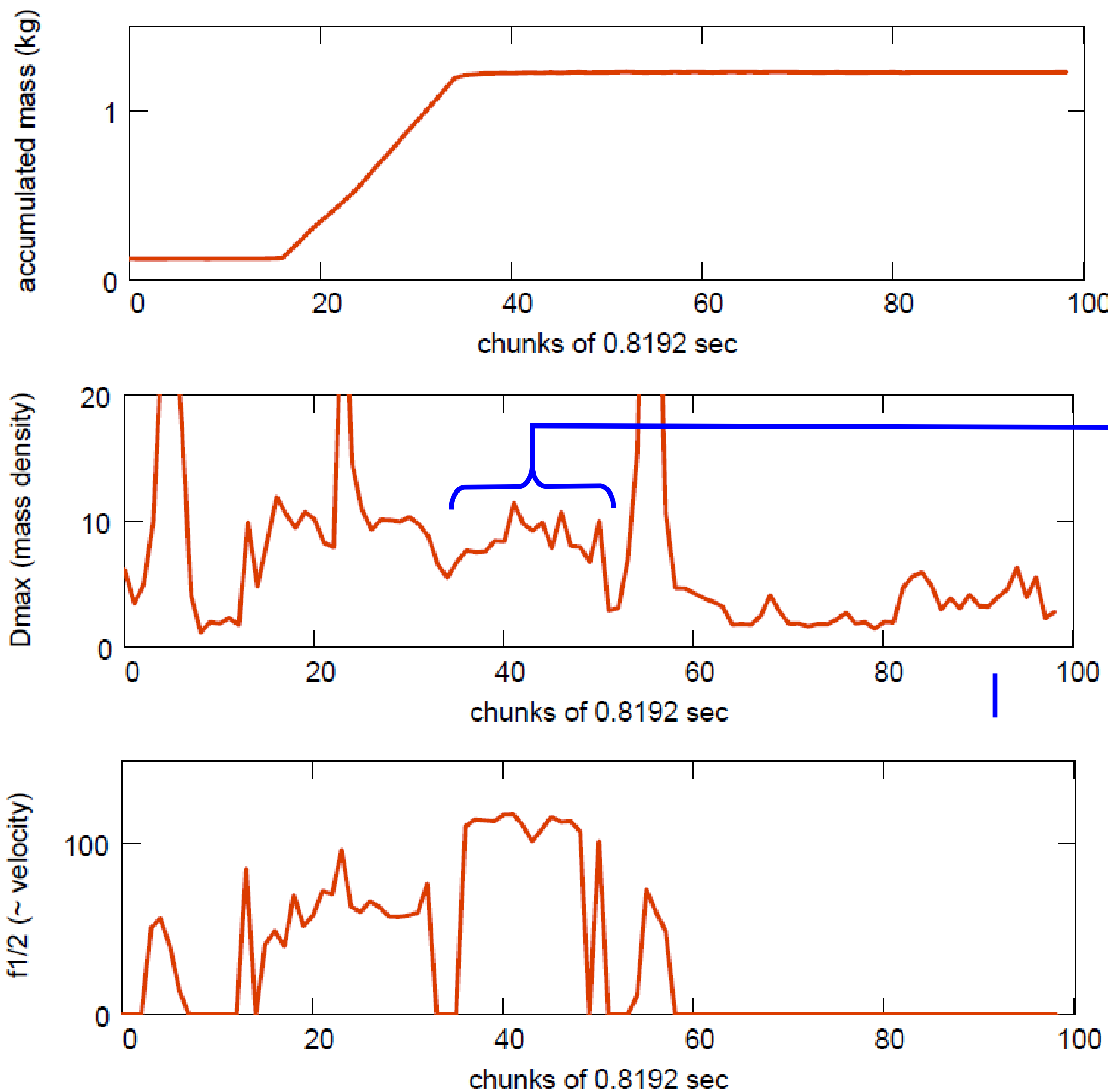
Some measurements- alumina launcher



- ilmenite
- varying motor speed
- 10 GHz
- 8192 points/ chunk
- 10000 samples/sec

- data processed and plotted in real time, samples stored after processing

Results from alumina launcher

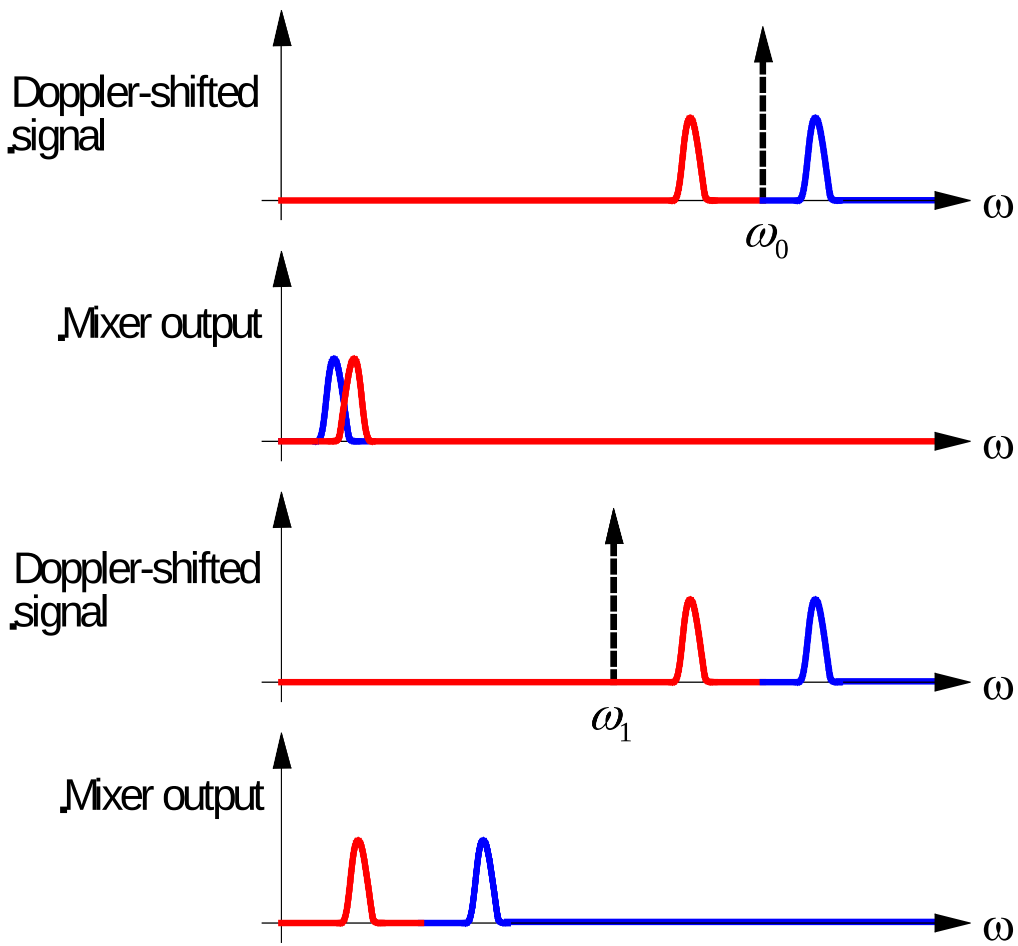


lower Doppler signal levels, higher reflected power

matching needs to be improved

table feeder vibration

An interesting possibility



- In the usual detection scheme both up and down velocities result in positive frequency shift
- Using an offset local oscillator, up and down velocities can be distinguished
- We can measure the entire velocity distribution function in a fluidized bed

Summary

- **Microwave Doppler can measure the average velocity and mass density independently**
- **Good results with testing**
  - continuous data analysis approach developed
  - continuous data analysis *implemented* and *tested*
- **Integration with NETL chemical looping reactor is in progress**