Laser Levitation:
Determination of Particle Reactivity

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Overview

- Project background and objectives
- Experimental methods
- Particle levitation model
  - Drag force model
  - Optical trapping mechanism
- Particle reactivity
- Conclusions

Background

- Optical manipulation of *transparent* particles reported by Ashkin in 1970
  - Optical tweezers used in aerosol and biological research
- Milliken oil drop experiment
  - Suspended small drops of oil between electrical plates to measure the charge of an electron

Background

- Electrodynamic levitation
  - Charged particles trapped in an electrodynamic chamber
  - Particles lose their charge at elevated temperatures
- Optical levitation of *opaque* particles reported in the early 1980’s
  - Not necessary to charge particles
  - To date, no mechanism has been established/accepted

Project Objectives

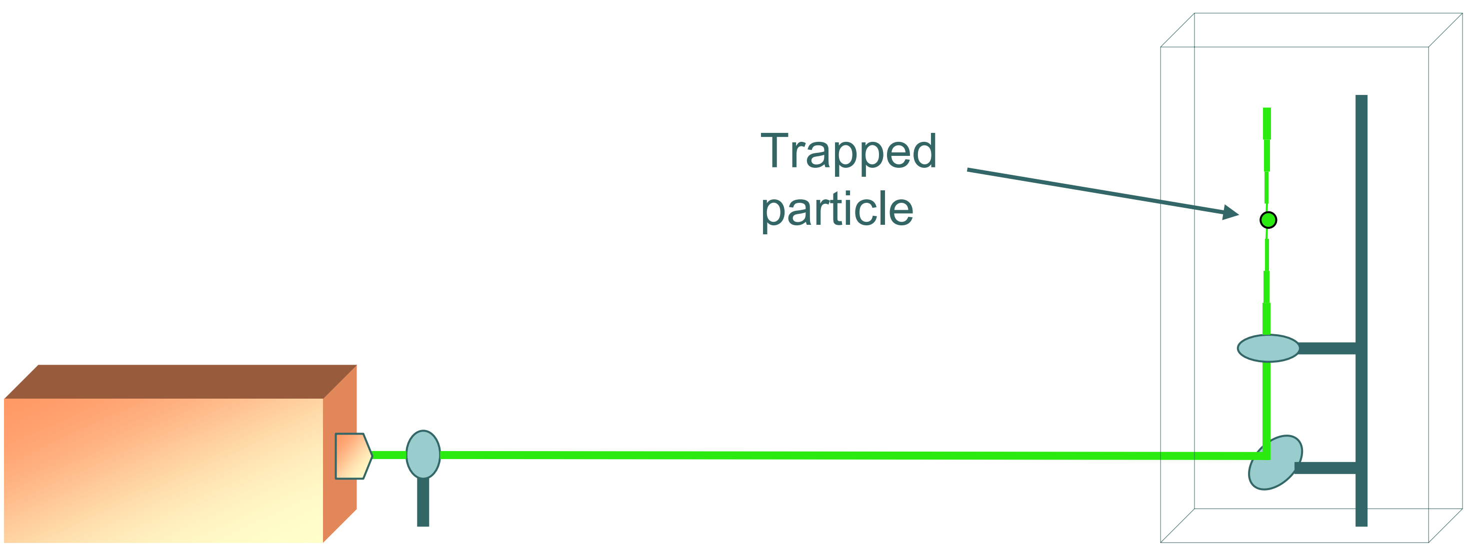
- Describe optical trapping mechanism
- Study combustion of single particles through entire combustion process
  - Model changes in the following variables:
    - Particle size
    - Surface temperature
    - Mass
    - Ambient pressure and gas composition
- Characterize reactivity of black liquor, coal, and other potential fuels

Experimental Methods

- Coherent Verdi V10 Nd:YVO_4 cw, 532 nm
  - Frequency-doubled beam
  - Variable power output up to 10.5 watts
- Ar^+, Nd:YAG, and Nd:YVO_4 laser beams successfully levitate particles

Experimental Methods

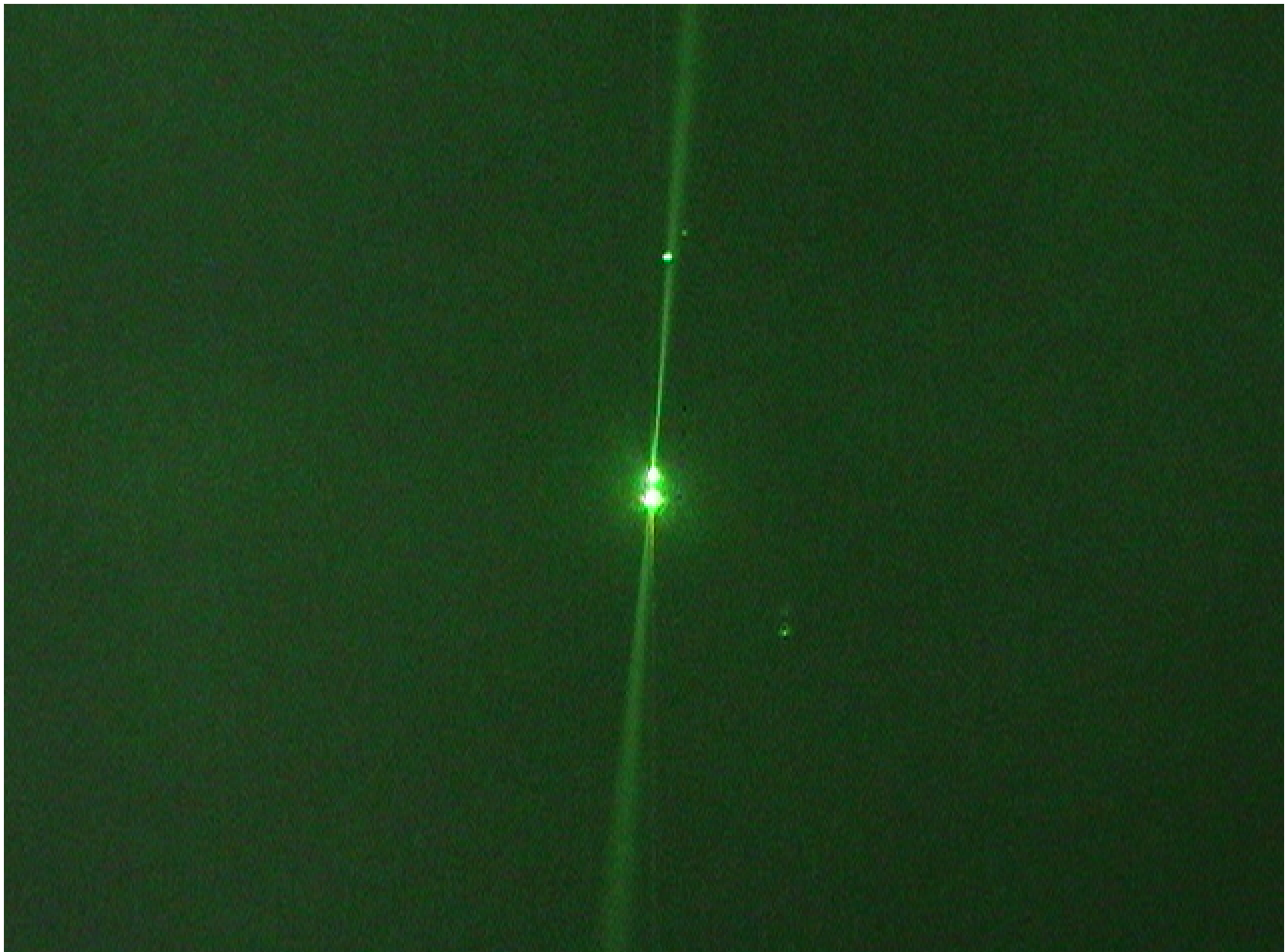
- 9-cm focal length lens focuses the beam
- A needle is coated with particles and passed through the beam near the focal point
- Enclosure inhibits rapid changes in air flow that otherwise convect particles out of the beam



Experimental Methods

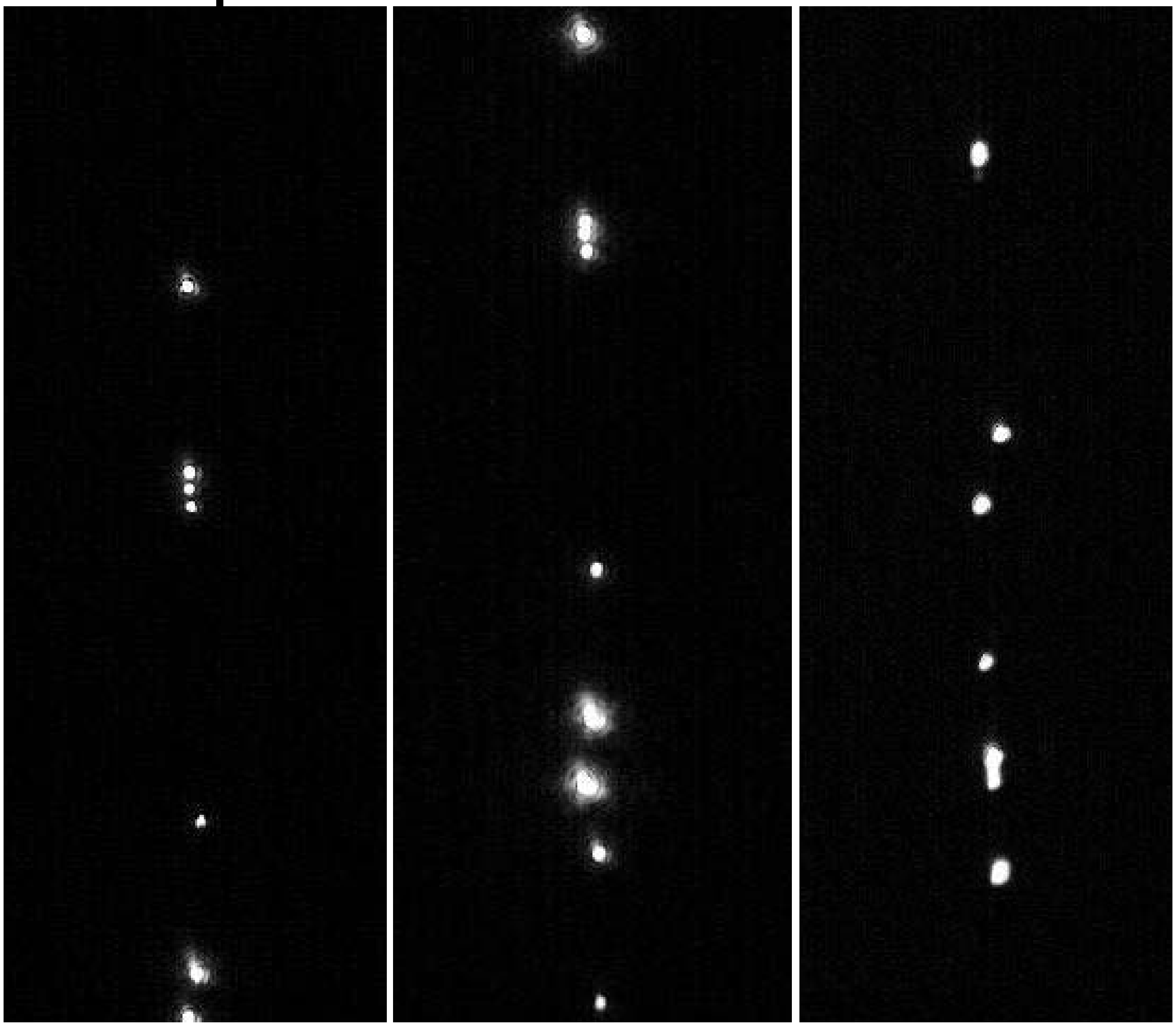
- Beams oriented in any direction successfully levitate particles
  - Vertical beams propagating upward are the most effective
- Experiments have been performed at ambient pressures as well as under vacuum
  - Cannot trap below ~1 torr

Trapped Particles



- Black liquor particles trapped at 2 watts

Trapped Particles



- Trapped black liquor particles at 2 watts of laser power
  - All particles shown are optically trapped
- Left and middle pictures are different views of the same case; the right picture is a separate case

Trapped Particles

Trapped Particles

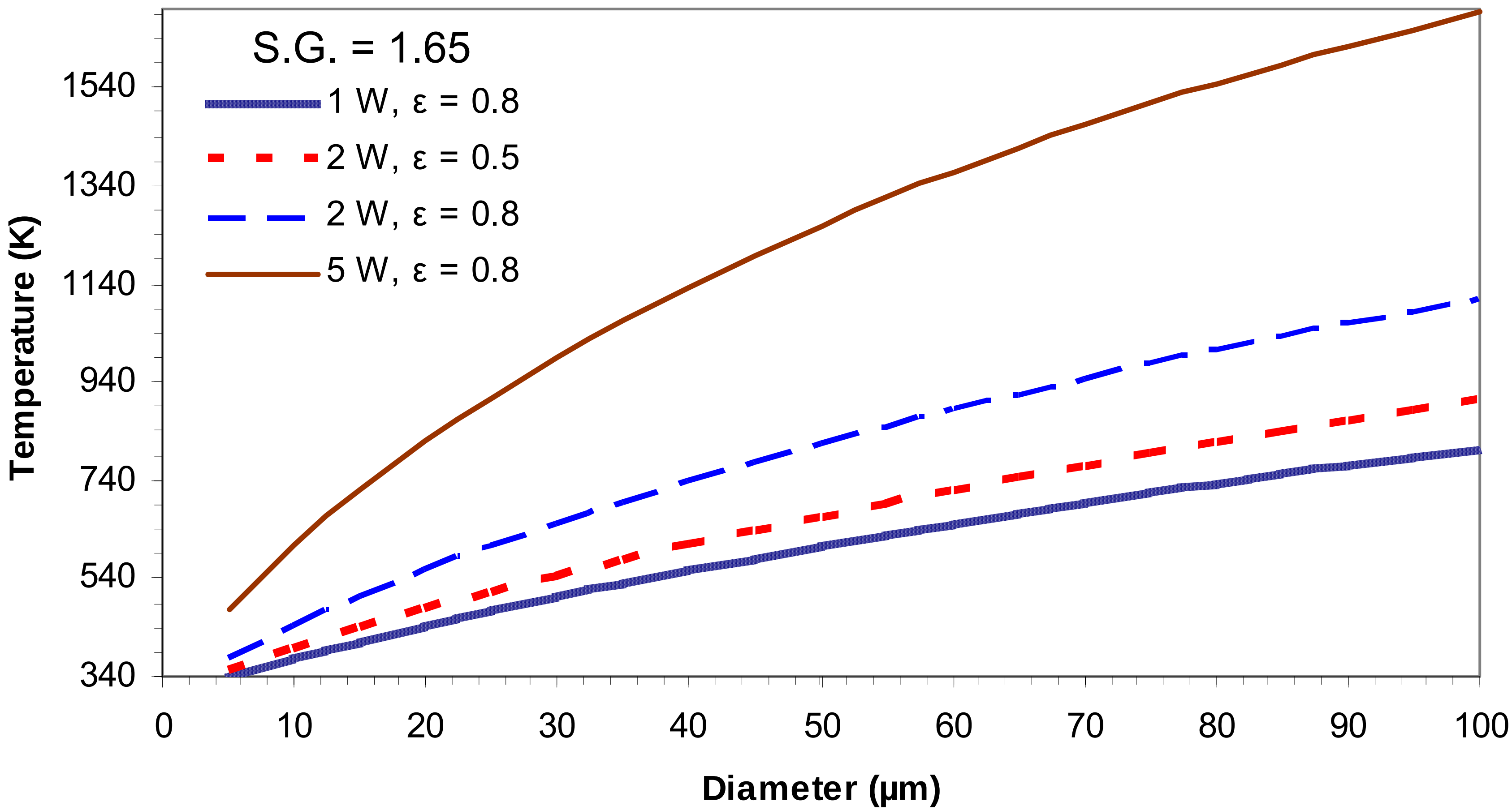
Particle Levitation Model

Energy Balance

- An energy balance provides estimates of particle surface temperature
  - Assumptions:
    - The only energy source is the incident laser light
    - The particles are inert
- Equates the heat from the laser light to the heat lost through convection and radiation

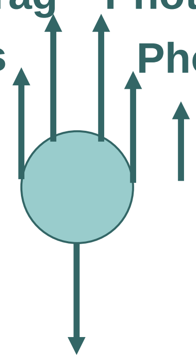
$$P_L \iint_{A_{p,cs}} S_L \, dA \cdot = A_{p,s} h (T_p - T_\infty) + A_{p,s} \varepsilon \sigma (T_p^4 - T_\infty^4)$$

Results of Energy Balance



Force Balance

- Force balance on particle includes 6 forces:



- Photon momentum
  - Each photon carries momentum equal to *h/λ*

$$F_{mom} = \varepsilon \cdot \frac{P_L}{c} \cdot \frac{A_{p.cs}}{A_{beam}}$$

- Photophoresis
  - Force due to heating from incident laser light
- Thermophoresis
  - Force due to a temperature gradient in the gas, i.e. hot to cold
- Buoyancy is negligible
  - More than four orders of magnitude smaller than the drag force

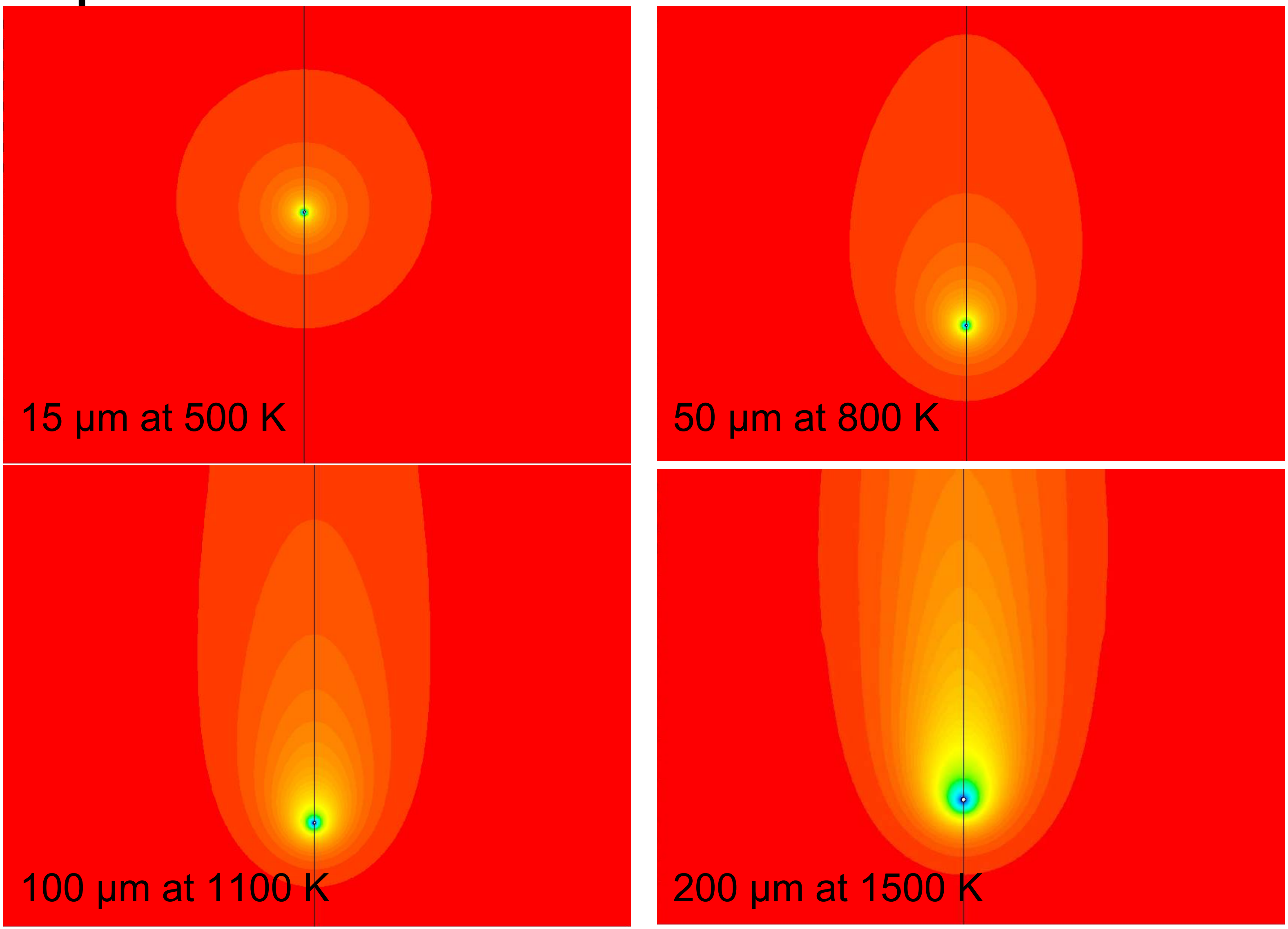
Force Balance

- Induced convective drag
  - Particle heats up due to incident laser light
  - Heating induces a convective flow around the particle
  - This flow generates a natural convective drag force
- Drag forces predicted with Fluent

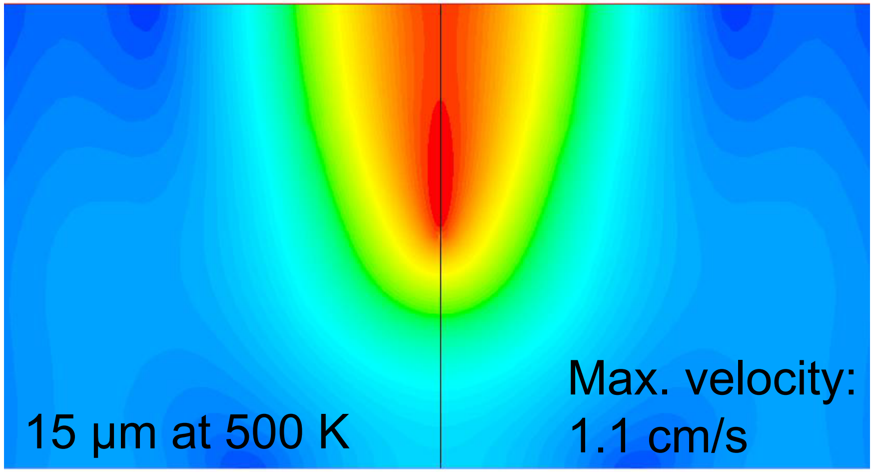
Drag Force Model

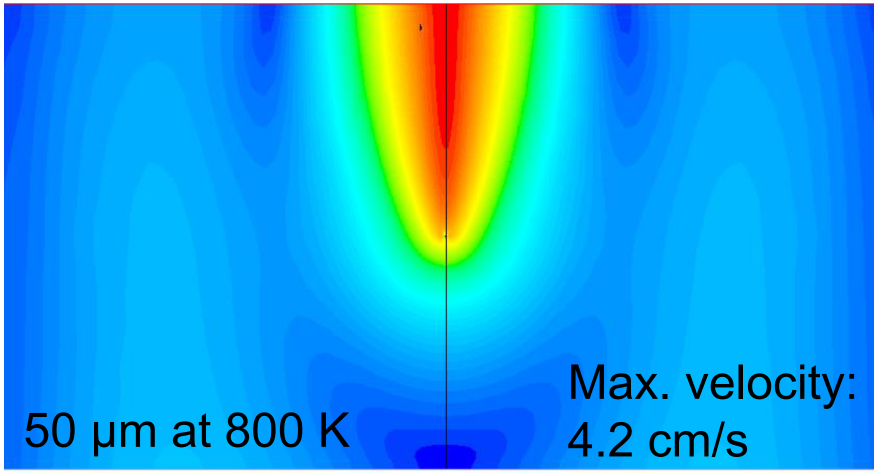
- Used Fluent™ and Gambit™ to predict the drag forces and to generate grids
- Modeled 5-200 μm particles at temperatures from 400-1700 K
  - Particles modeled as isothermal spheres
- Photophoretic, thermophoretic, and light momentum force calculated separately

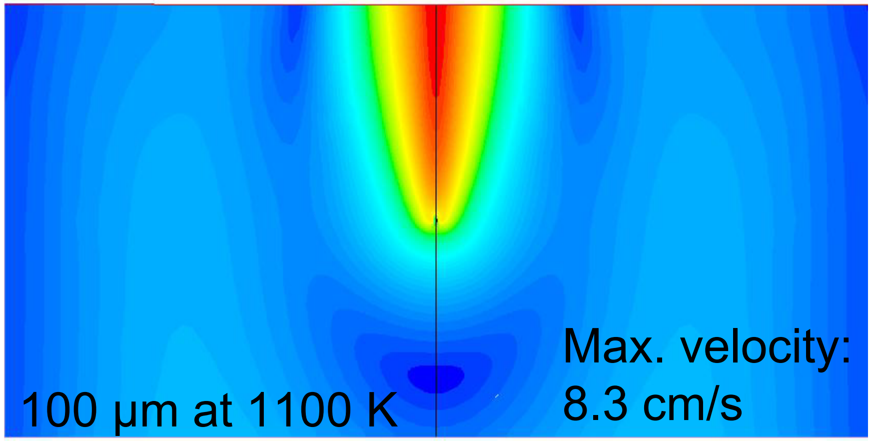
Density Contours

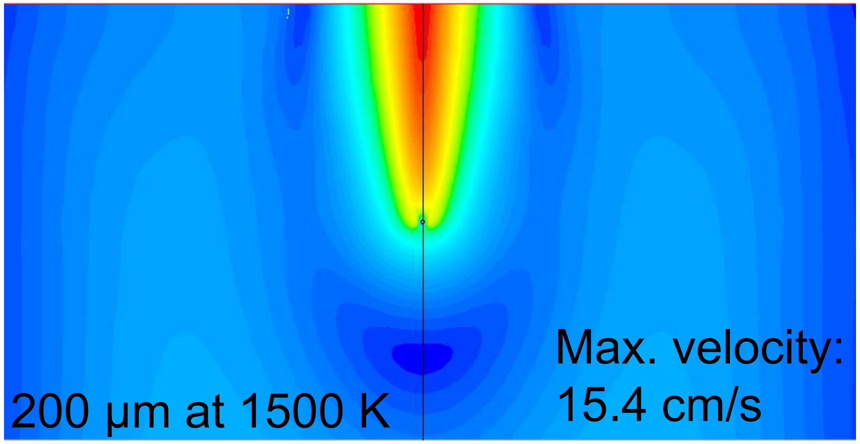


Velocity Contours

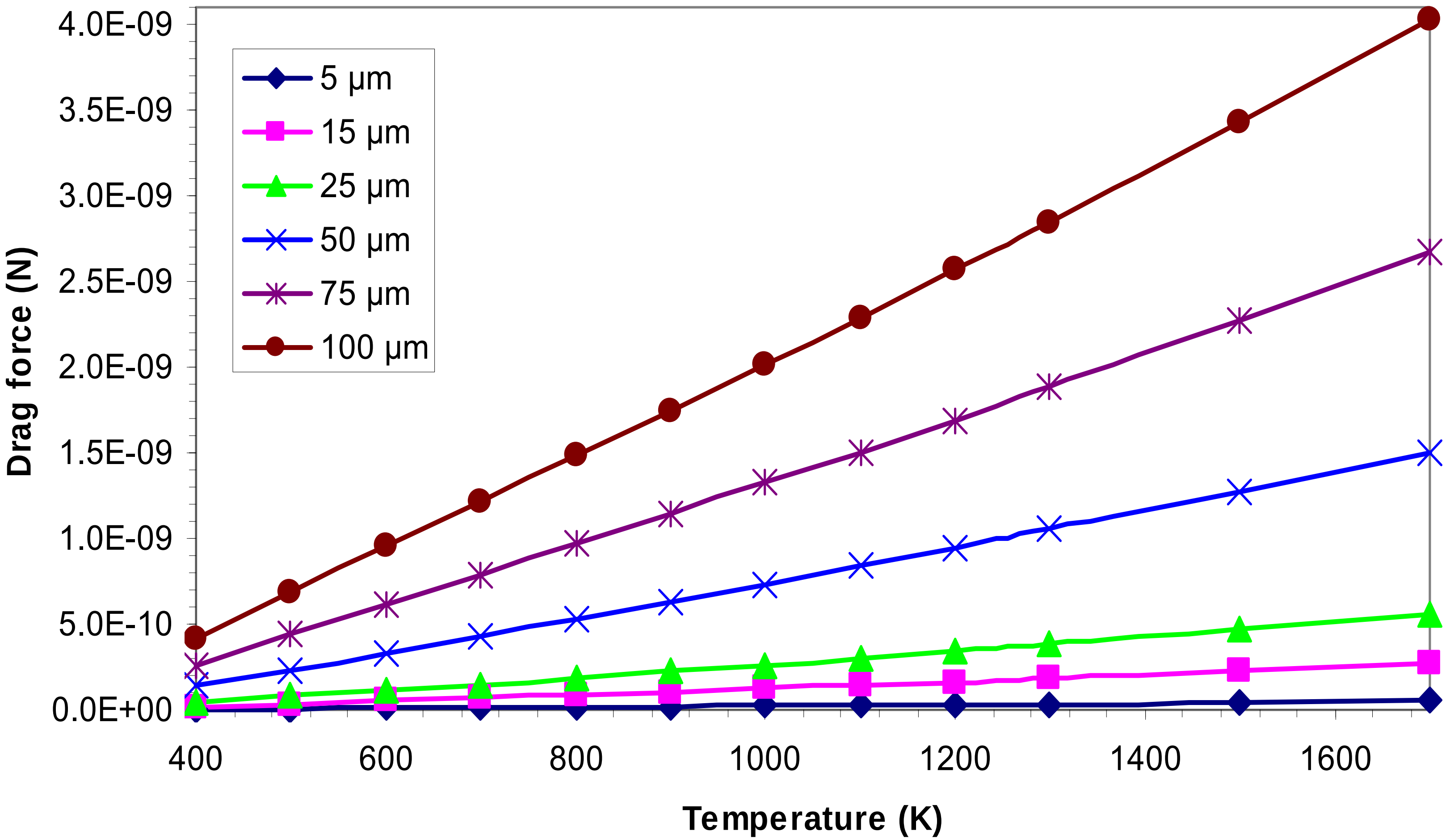




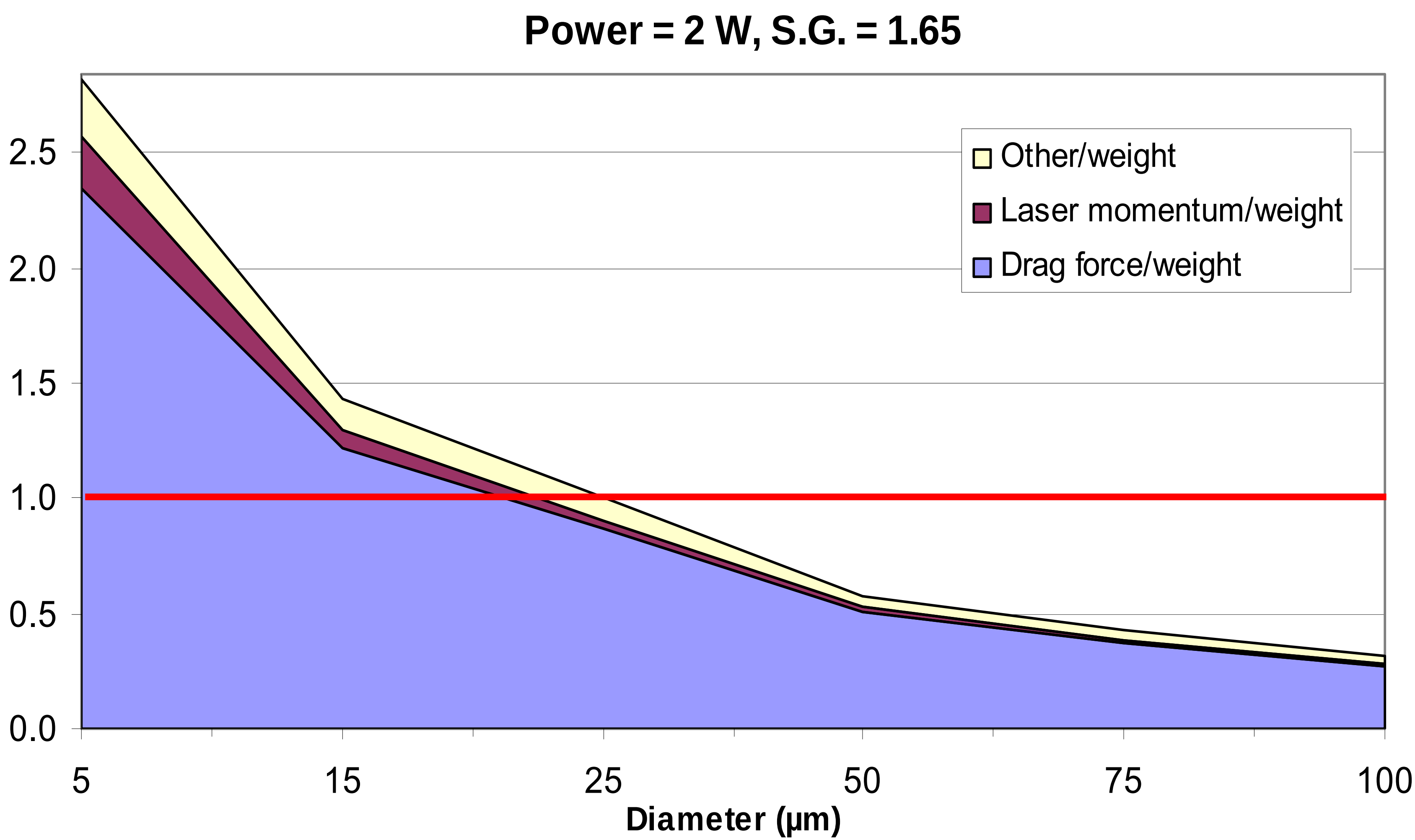




Drag Force Predictions

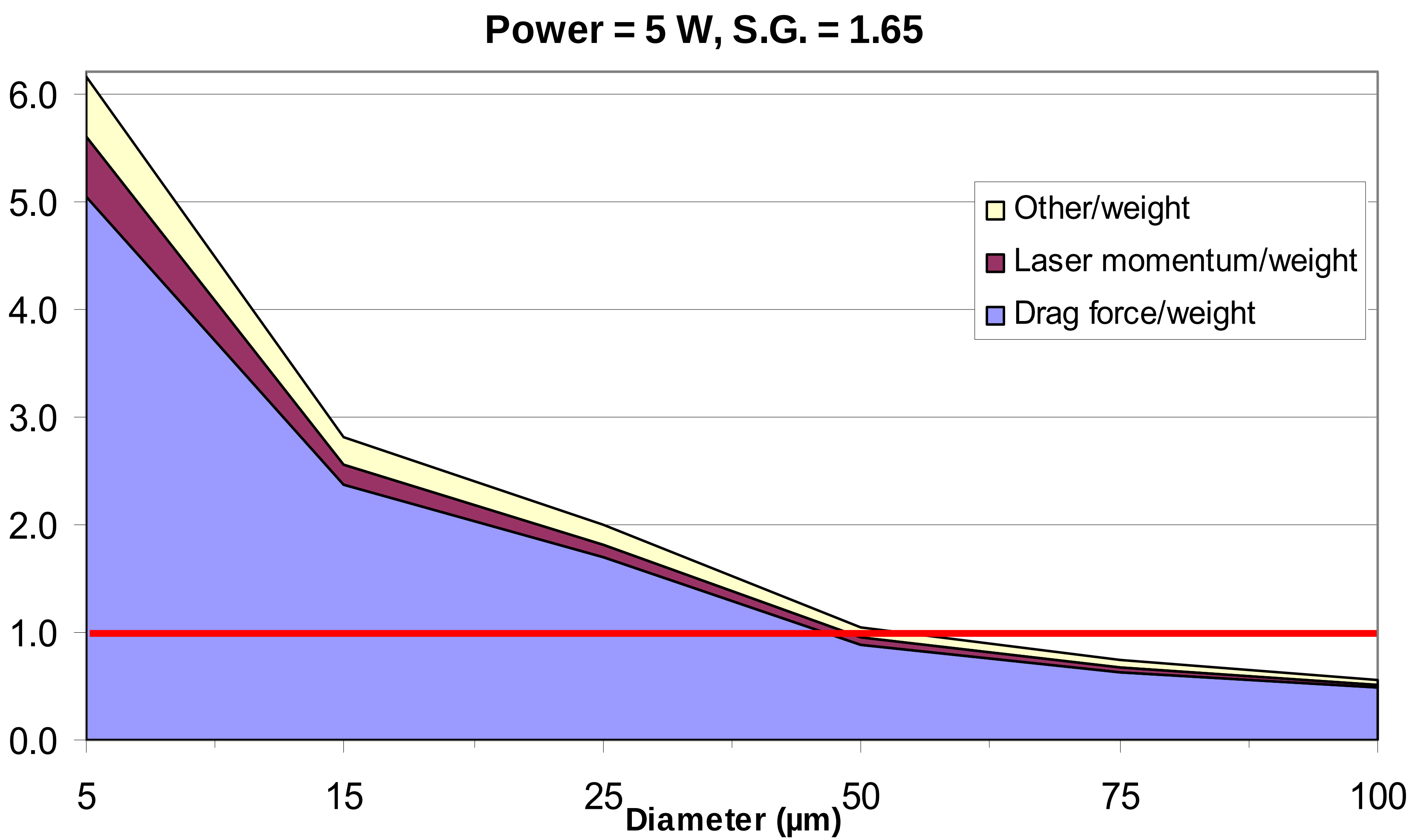


Analysis



Power = 2 W, S.G. = 1.65
2.5
2.0
1.5
1.0
0.5
0.0
5
15
25
50
75
100
Diameter (μm)
Other/weight
Laser momentum/weight
Drag force/weight

Analysis



Power = 5 W, S.G. = 1.65
6.0
5.0
4.0
3.0
2.0
1.0
0.0
5
15
25
50
75
100
Diameter (μm)
Other/weight
Laser momentum/weight
Drag force/weight

Conclusion/Application

- Combination of drag, gravity, and other forces equilibrate, trapping the particle
- Depending on the laser power and particle density, we can trap particles up to ~50 μm
- We are able to suspend various types of particles under arbitrary conditions
  - Technique works under a range of pressures and ambient gas composition

Conclusion/Application

- Using diagnostic techniques we will be able to continuously measure particle temperature, emissivity, size, and shape
- How can we use this information?
  - This will allow determination of particle reactivity as a function of time
    - Particle temperature
    - Reaction enthalpy

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