Fluorescence-Doped Particles for Simultaneous Temperature and Velocity Imaging

Principle Investigators:

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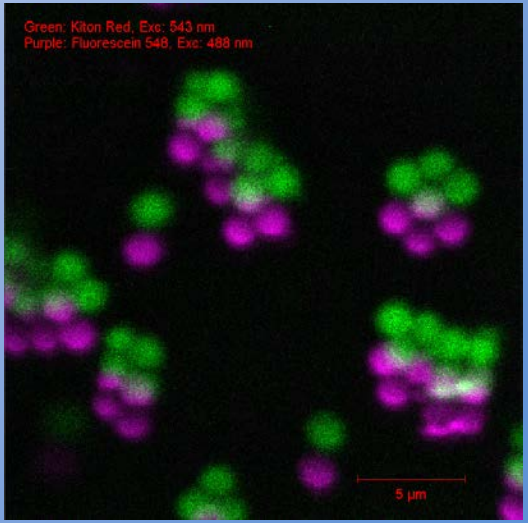
Additional Team Members:

T. Lowe and R. Simpson (Va Tech)



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Outline

- Current state of the art
- Technical approach
- The innovation: key points
- Impact of the innovation if it is eventually implemented
- Results of the seedling Phase I effort to date
- Distribution/Dissemination – getting the word out
- Next steps

Current state of the art

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- Most common measurements in wind tunnels are lift, drag, force and moment
  - Also: surface pressure, surface heat transfer
- Off body, most common techniques:
  - Schlieren, non-quantitative flow vis
  - Laser Doppler velocimetry (LDV), u, v … oint
  - Particle Image Velocime…), u, v in a plane
- Measurements <u>not</u> readily available:
  - In stream temperature, pressure, concentration

Easy to use, turn key, safe

Need: Easy to use, turn key, safe

Why Use Particles?

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- Other ways of measuring flow temperature (without seeding particles) exist, but have limitations preventing their use:
  - CARS: complicated, expensive, hard to set up, single point, 10 Hz
  - Rayleigh/Raman scattering: low signal, complicated to analyze, often single point, 10 Hz
  - PLIF: must seed flow with (usually) toxic gas, complicated, not very accurate, not sensitive enough, 10 Hz
  - Thermocouple: intrusive probe, single point, slow time response
- Few or no viable methods of measuring flow pressure exist
- Seeding dye-doped particles into a flow to measure *T*, *P*, and/or stream concentration should allow high s/n images
  - Easy because uses same or similar lasers, seeding systems, detectors as PIV/LDV → prefer imaging, non-toxic seeding
  - Performing in conjunction with PIV/LDV will measure multi-parameters

Technical Approach: Measure T

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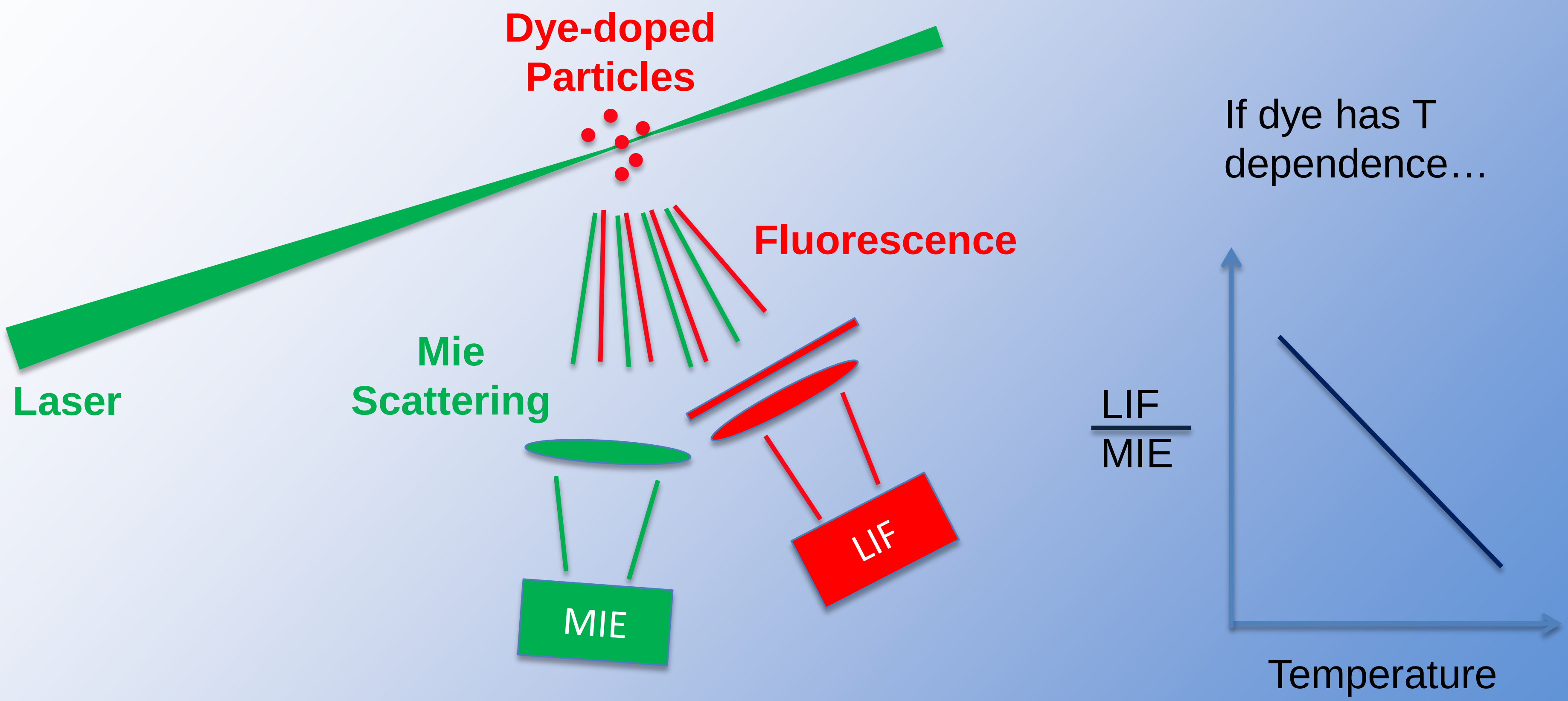

Temperature (only) Measurement Approach

Technical Approach: Measure P

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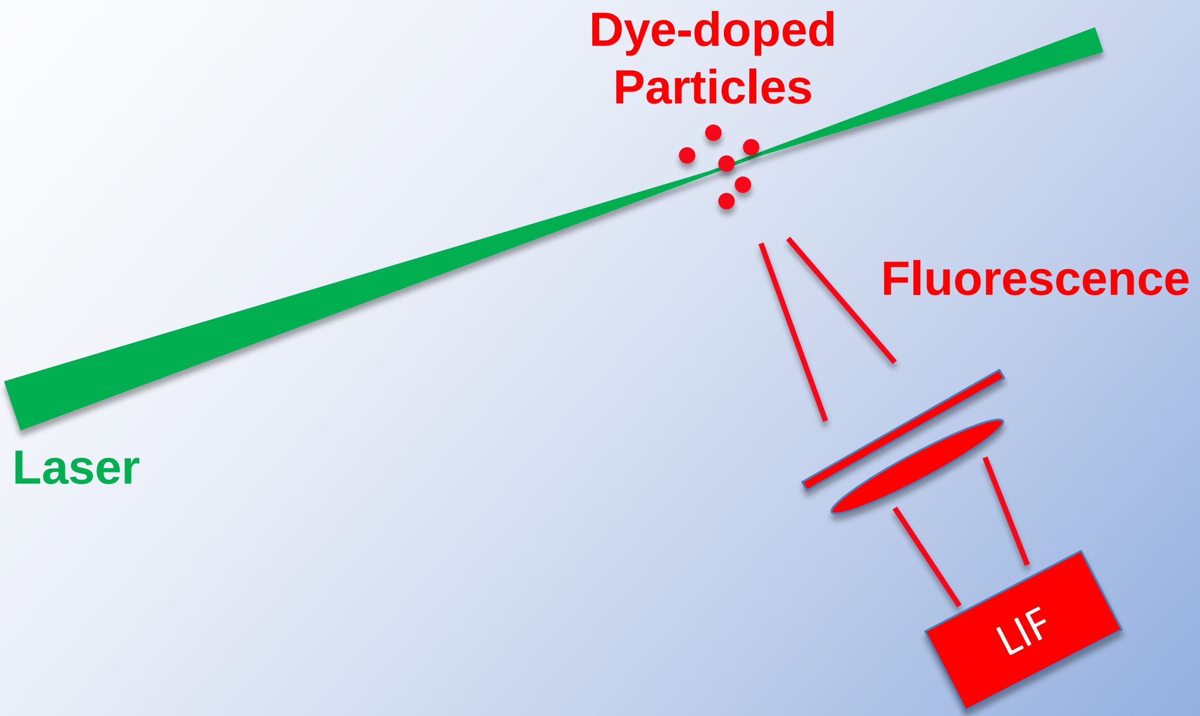
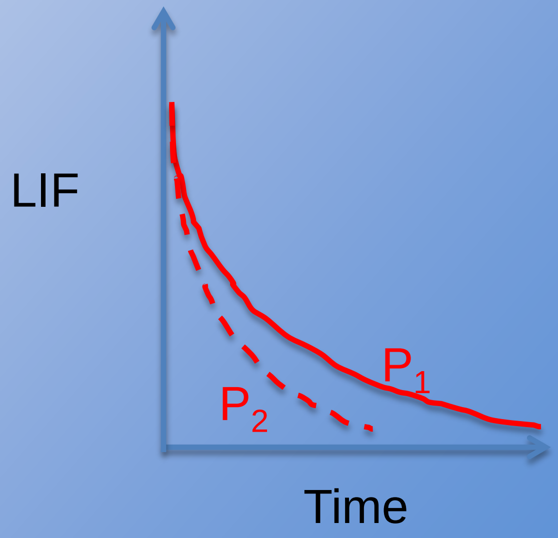
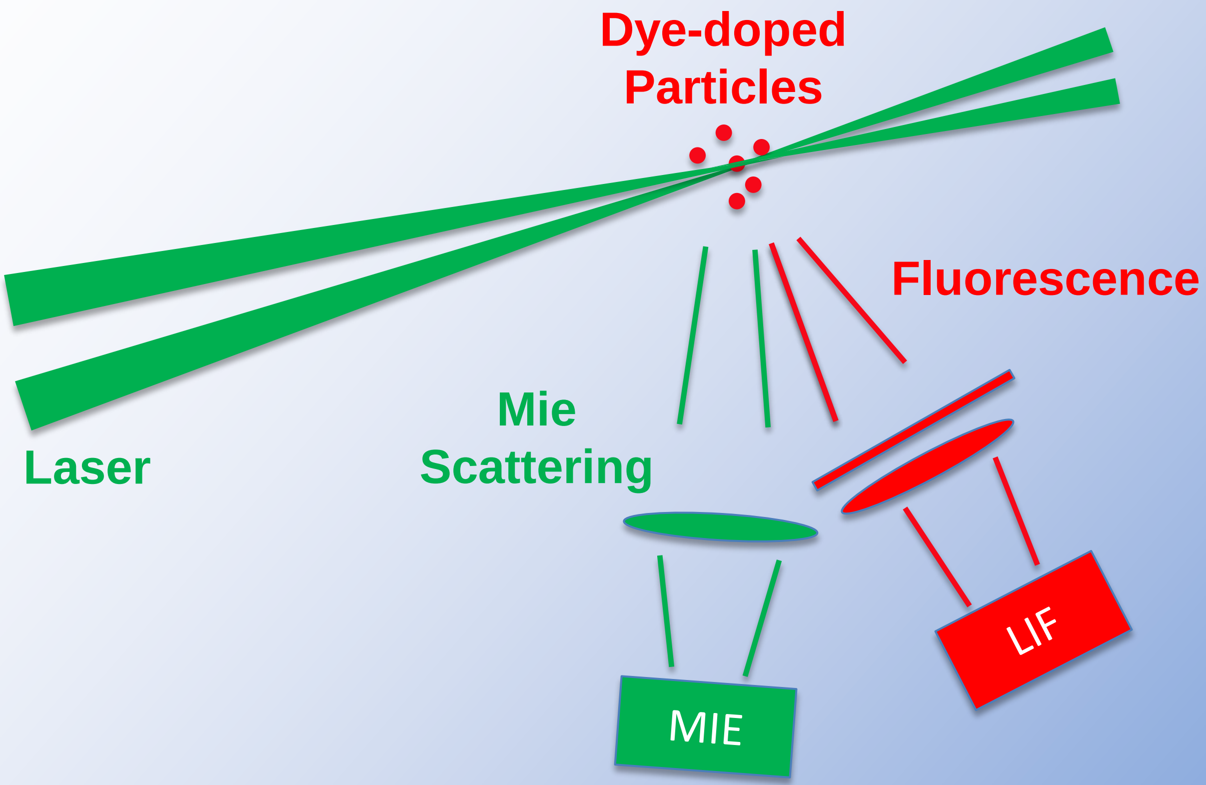


Dye fluorescence lifetime depends on pressure…

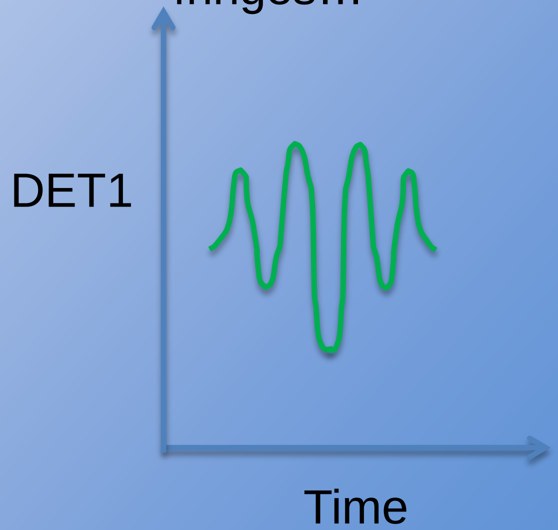


Pressure (only) Measurement Approach using Lifetime Measurement (could also measure intensity of signal referenced to Mie)

Technical Approach: Combine w' LDV



Measure velocity from frequency of collected light from particle passing through fringes…



Measure velocity from LDV, Pressure or Temperature from fluorescence

Technical Approach: Imaging Example

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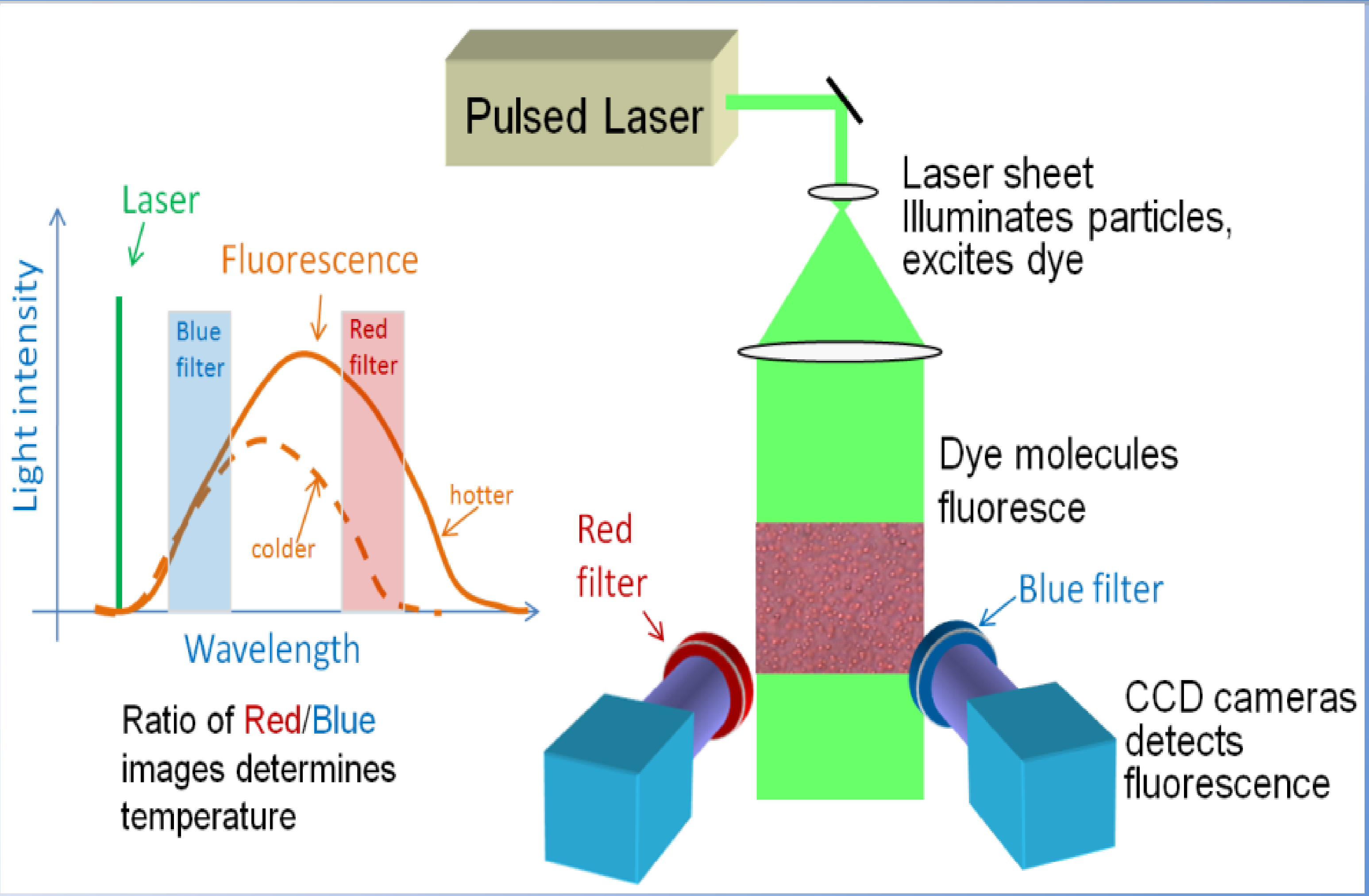

Combine T, P or concentration measurement with Particle Image Velocimetry (PIV)

Technical Approach: PSLs

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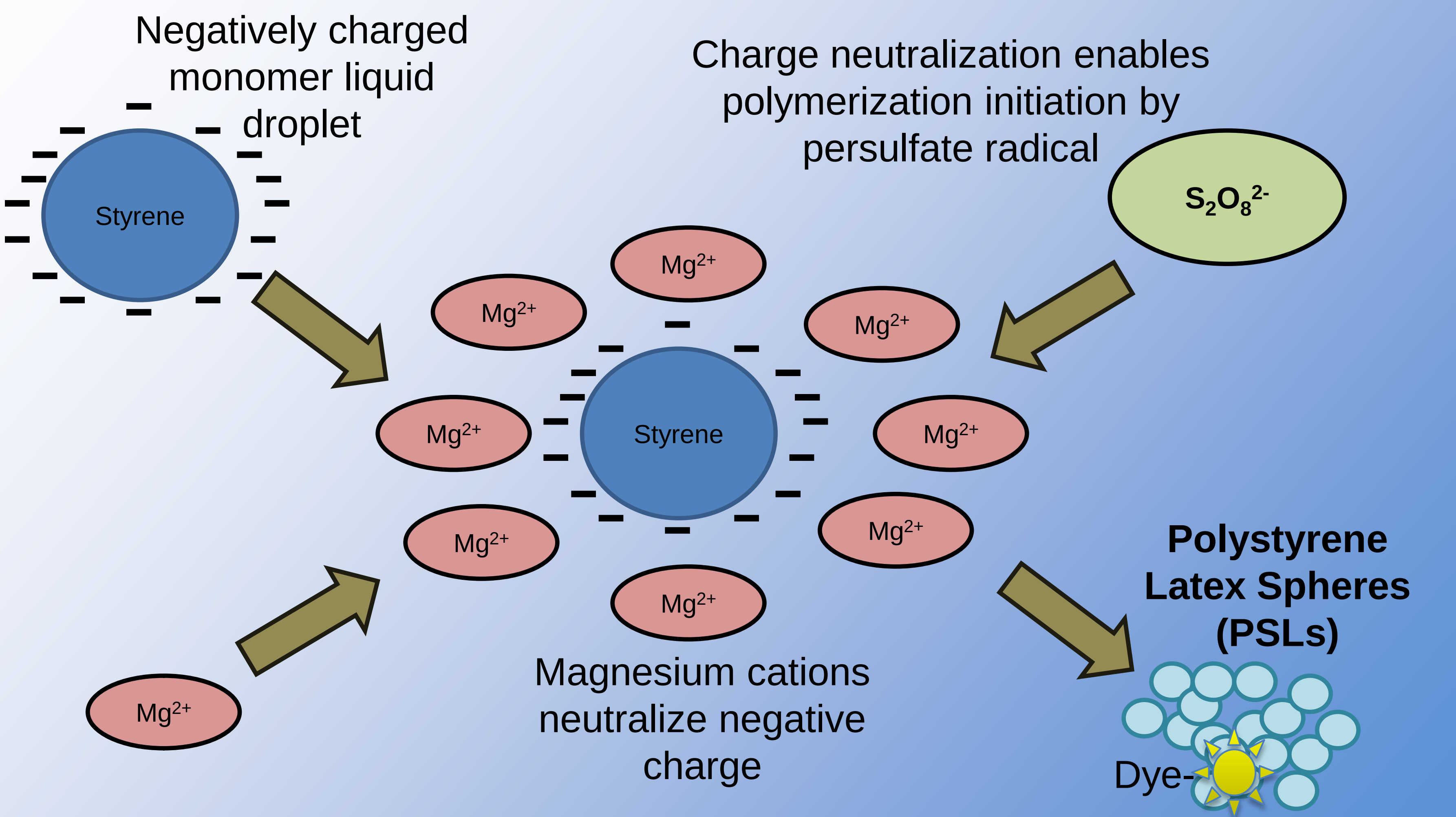

How do we attach the dye?

Technical Approach: Dye Doping

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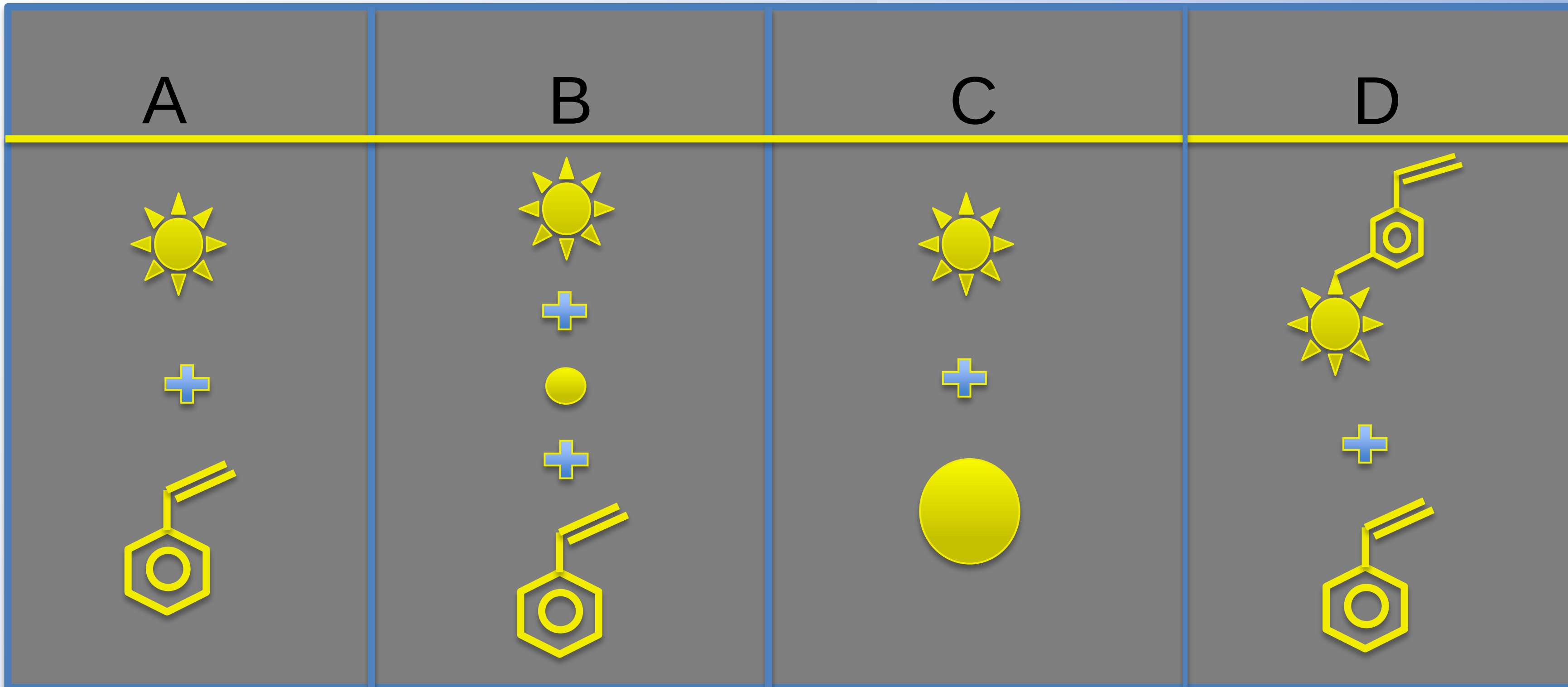
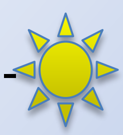
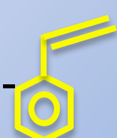
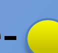
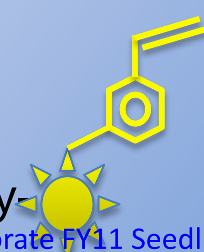


Dye- 

Styrene- 

Premature Particle- 

Dye with a Styrene functionality- 

Mature Particle- 

Technical Approach: Dye Doping

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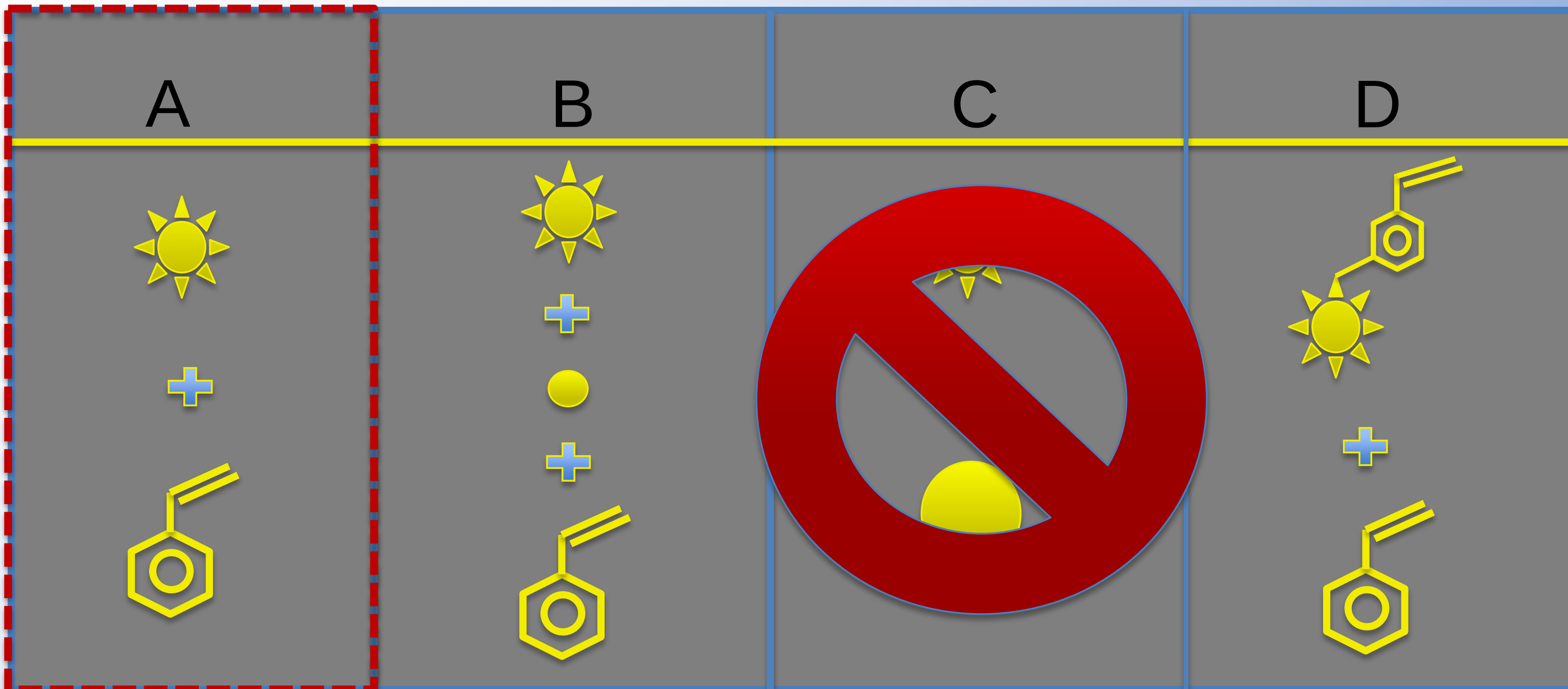

Innovation: Key Points

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- Have identified multiple measurement approaches with different dyes and different laser and detector configurations to measure:
  - Temperature, Pressure, Concentration
  - Pointwise (fast) or imaging (10 Hz) are possible
  - Alone or simultaneous with LDV, PIV
- PSLs have been synthesized with an array of dye materials with varying degrees of success
  - Dye influence on particle size and size distribution was observed and characterized
  - Different methods of incorporating dyes explored
- Temperature measurement in a flow experiment was demonstrated with (VT, POC: Todd Lowe)

Impact of Innovation if Incorporated

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- **Extend measurement technology beyond force/moment/wall and u, v velocity measurements**
  - Temperature, Pressure, Concentration
- Impact on NASA ARMD Programs:
  - <u>SFW/ERA</u>: Jet noise studies, T, u, v and correlations
  - <u>Rotary Wing</u>: Pressure disturbances near blade tips
  - <u>High Speed</u>: Sonic Boom simultaneous P, u, v measurement
  - Measurements would provide unique data for validating CFD codes in a way not currently possible.
- Have identified potential customers within NASA, at other government agencies, academia and industry.

Phase I Results

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- Dye materials evaluated

Dye	λ_{exc}, nm	λ_{em}, nm	PSL Incorporation	notes
Rhodamine B	575	595	Great, no leaching	Potentially carcinogenic
Fluorescein 548	512	526	Solvent dependent emission	Non-carcinogenic
Kiton Red 620	554	575	Leaching issues	Non-carcinogenic
Tetraphenyl Porphyrin	400	655	Inefficient incorporation	Tunable spectral properties

Other materials evaluted including fluorenone, 4-hydroxycoumarin, and Malachite Green.

Phase I Results: Rh B

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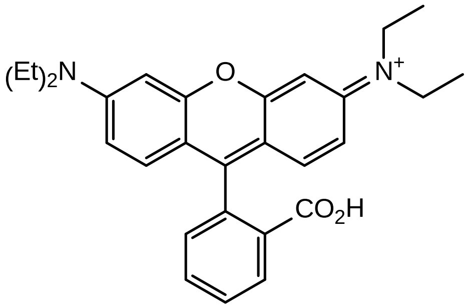
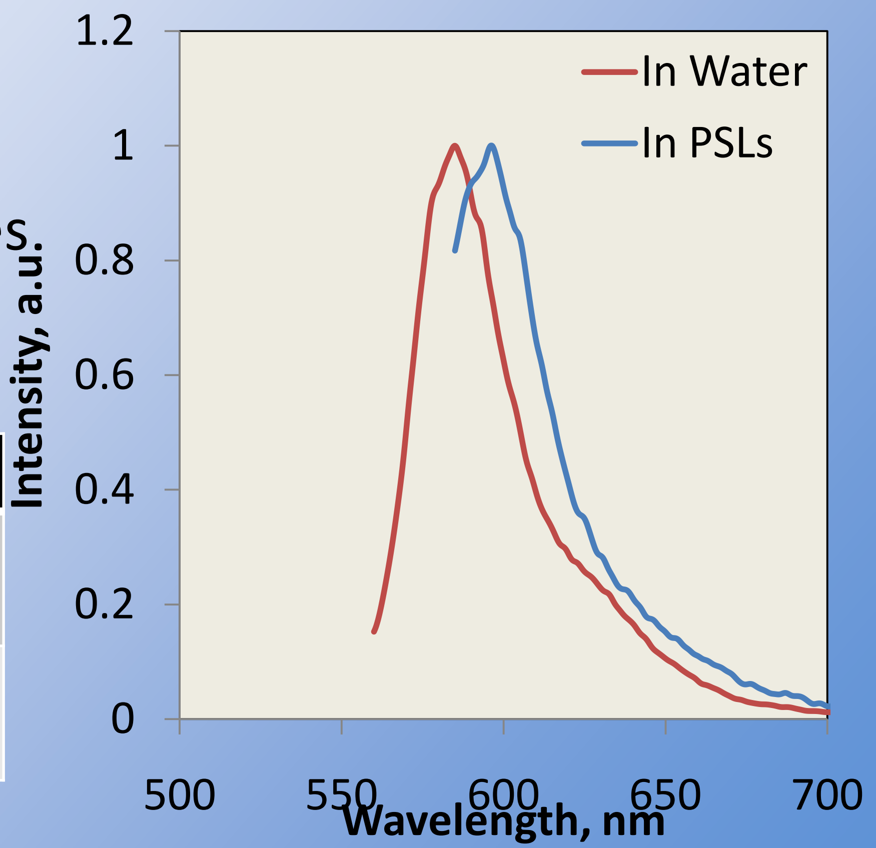


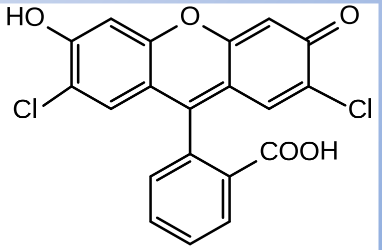
- **Rhodamine B: Very strong Signal**
  - But slightly toxic
- Spectrum shifts in PSLs: Excitation and emission properties of Rhodamine dyes are strongly dependent on matrix properties

	In Water	In PSLs
Excitation Maximum	546 nm	575 nm
Emission Maximum	585 nm	595 nm



- Decreases particle size ~10%

Phase I Results: FL548



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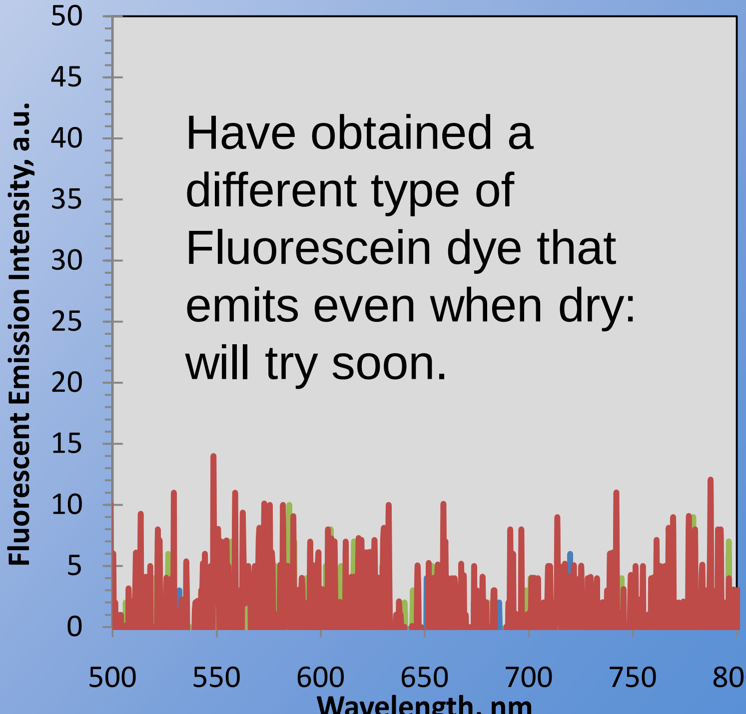
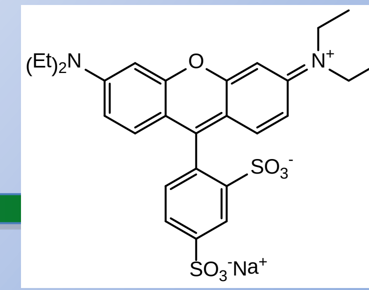
- Fluorescein 548
  - Showed good signal and temperature sensitivity in preliminary tests
  - Shows Complex Emission/Quantum Yield Behavior

- Excitation at 532 nm.
- Emission intensity diminishes significantly and rapidly as solution evaporated.
- No detectable signal after the deposited PSLs were allowed to dry. ⟶



Phase I Results: KR



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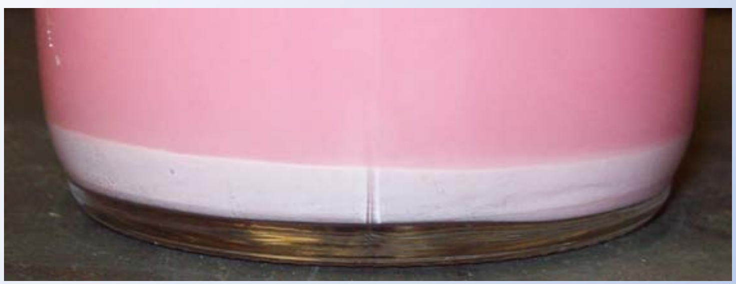
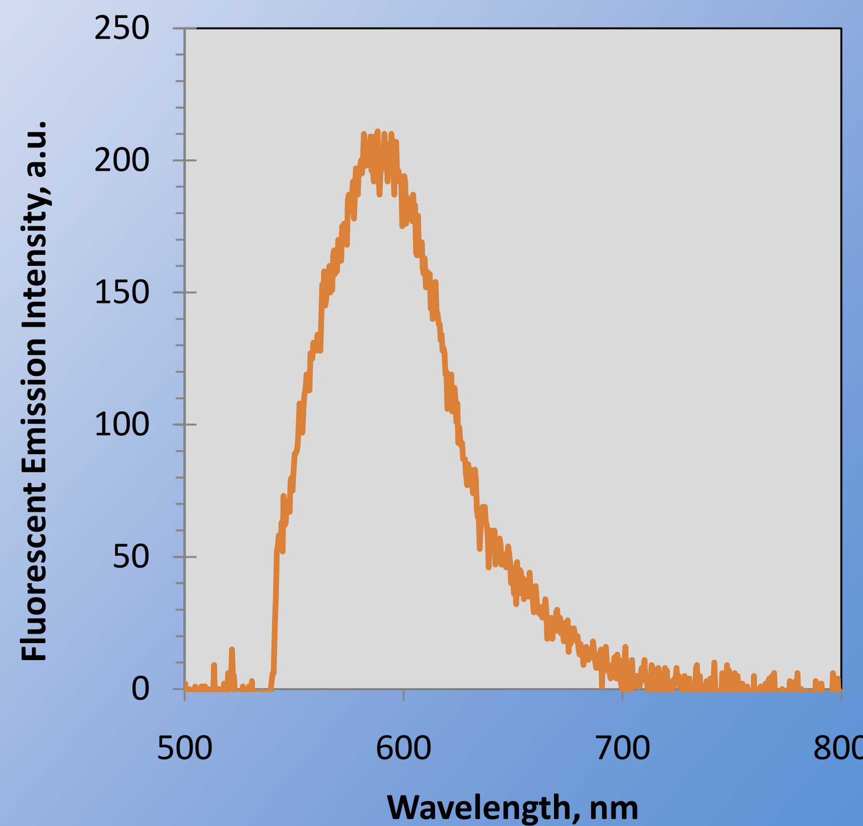
- Kiton Red
  - Less Toxic than Rh B
  - Lower signal than Rh B
  - Better for concentration meas.
  - Dye Leaching out:



- Once PSLs have settled, there is a clear distinction in color between the PSLs (white) and aqueous solution (red).



Phase I Results: Leaching

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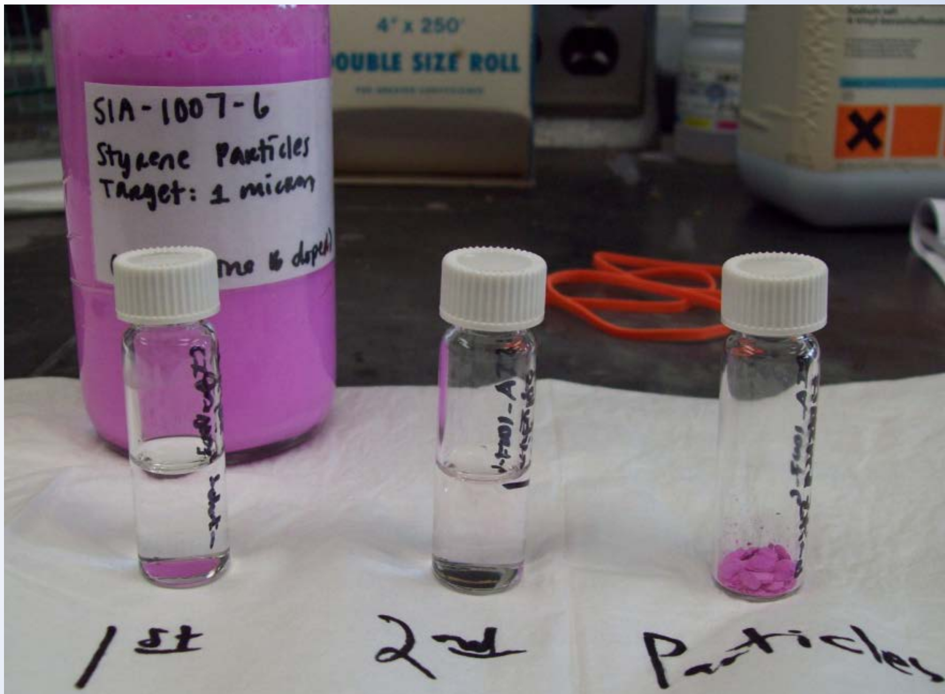
- Leaching Studies

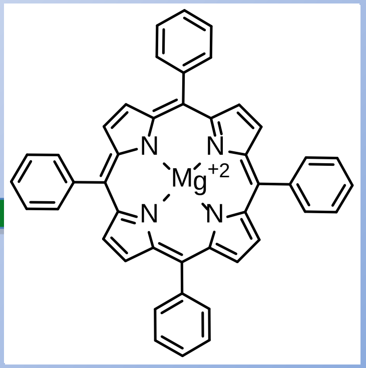


Rhodamine B-doped PSLs

Kiton Red-doped PSLs

Even if Rh B is slightly toxic, if it is encapsulated in a polymer and won't leach out (in water), might it be acceptable for use?

Phase I Results: Porphyrin



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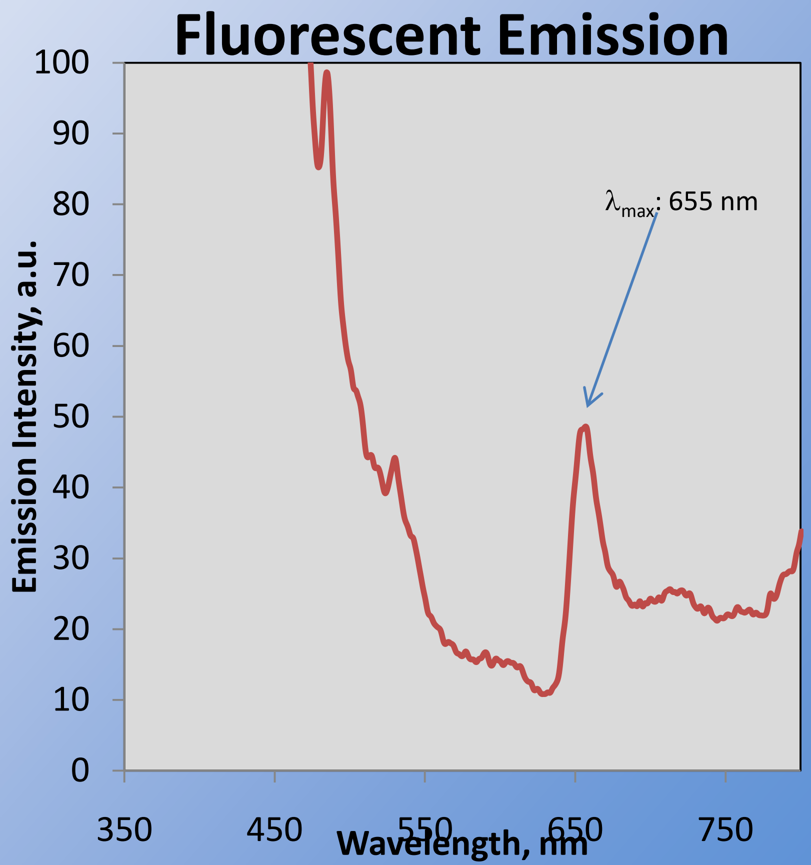
Porphyrin

-Suitable for pressure measurement

-So far, low signal intensity

Complex Spectroscopic Properties:

- Coordination of an ion in the center of the macrocycle impacts:
  - Fluorescent emission
  - Quantum yield
  - Phosphorescent properties
  - Propensity for PSL incorporation?
- PSL synthesis uses $MgSO_4$ resulting in formation of a Mg-TPP adduct: Chlorophyll-like



Phase I Results: Concept Demo I

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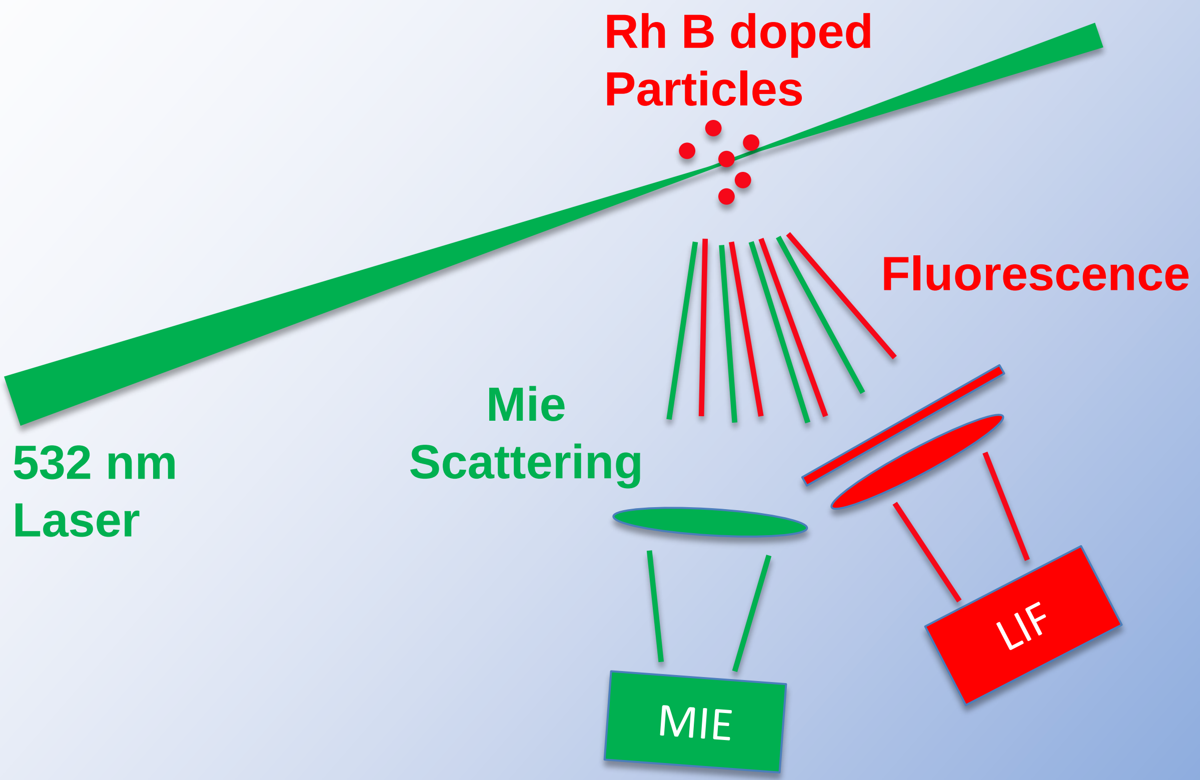

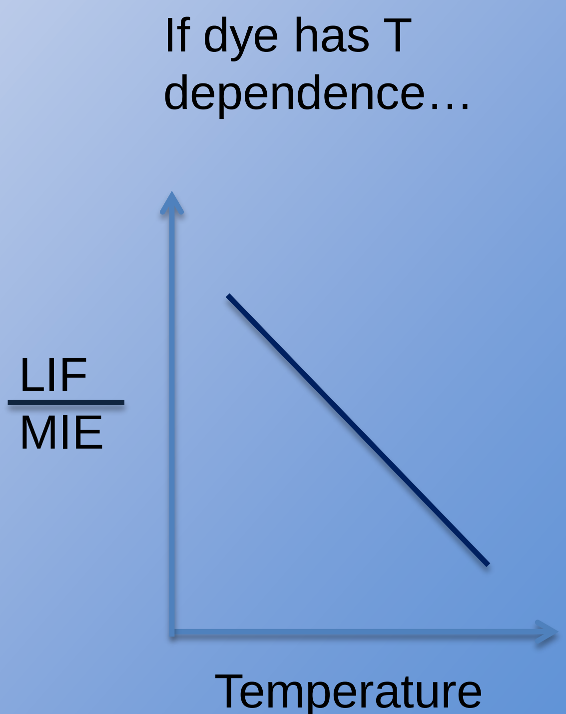

Va Tech demonstration used first measurement approach described above

(Lowe, VT)

Phase I Results: Concept Demo II

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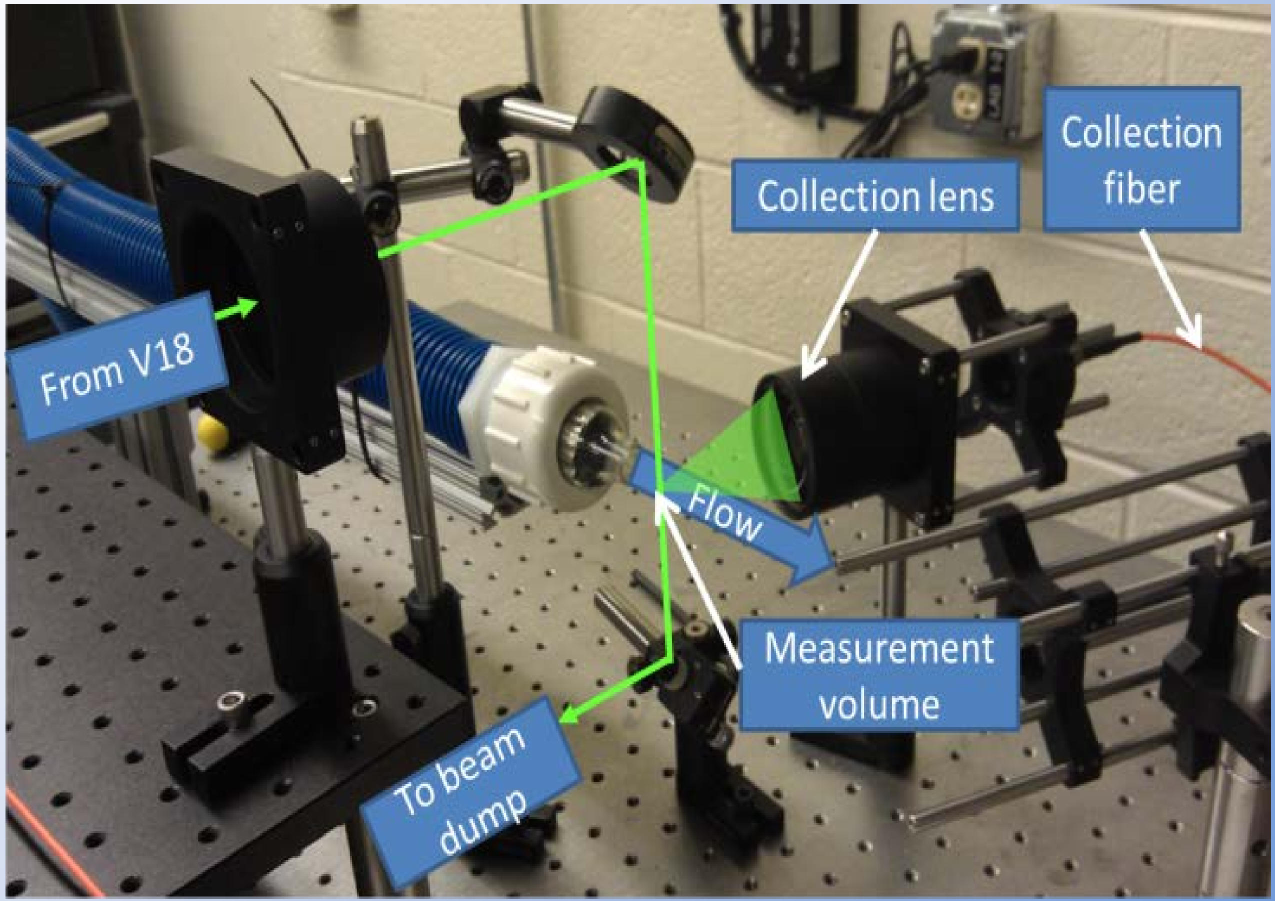
5 W laser



PMT detection

(Lowe, VT)

- Split collected light into two channels: Mie (532 nm) & LIF (>600 nm)
- Added dry ice to flow to vary temperature; monitor with thermocouple

Phase I Results: Concept Demo III

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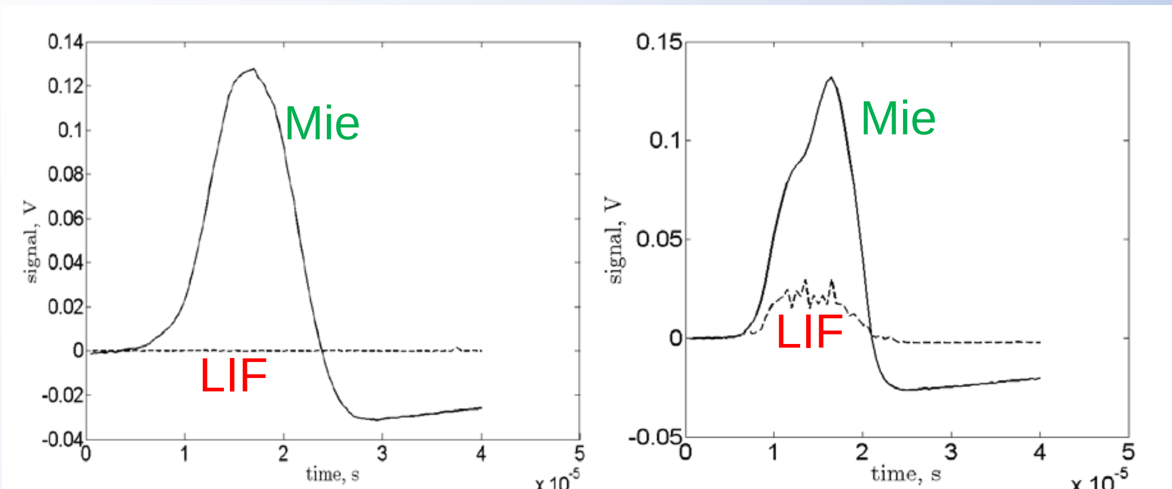
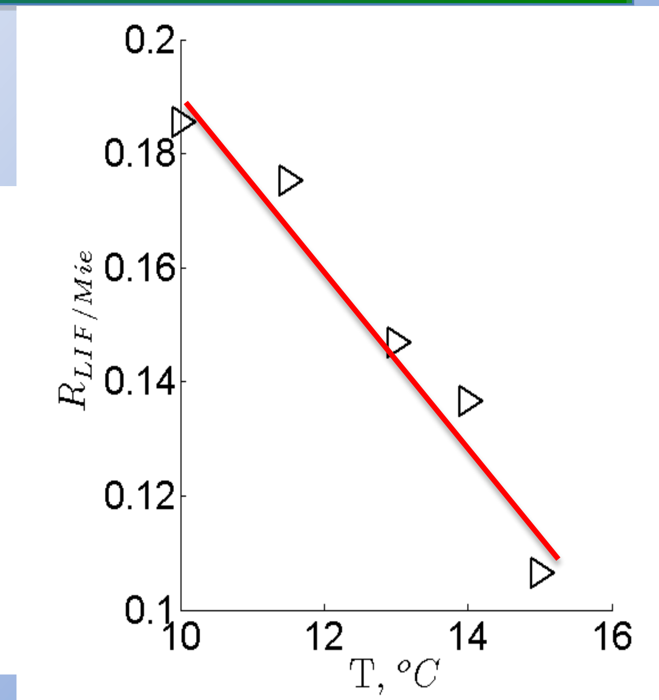
Scattering traces from single particles

No dye in PSL: With dye in PSL:





- Mie scattering provided plenty of signal for velocimetry (though not demonstrated in this experiment).
- LIF channel provided sufficient signal for temperature determination (using Mie as reference)
- Temperature range in proposed experiments will be larger

(Lowe, VT)

Distribution: Getting the Word Out

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- Presentations:
  - Occurred: SERMACS-2011
  - Planned:
    - ACS, MRS, or Equivalent for materials synthesis
    - AIAA meeting with PSL seeding characterization results
- Publications:
  - Demonstration work at VT is nearing conference/journal publication quality results
  - PI's have strong track record of publishing in conferences and journals (see proposal appx)

Proposed Budget

Proposal Title: *Fluorescence-Doped Particles for Simultaneous Temperature and Velocity Imaging*

From: *07/01/12*
To: *12/31/14*

PI's Name: *Paul Danehy*

NASA Center: *LaRC*

Assume $150K for 1 Full Time Equivalent of 2080 hours per NASA Civil Servant.

Budget Request ($K)	**FY12**	**FY13**	**FY14**	**TOTAL**
Civil Servant Salary: *Paul Danehy PI (0.15 FTE)*	*6*	*22*	*6*	34
Civil Servant Salary: *Patsy Tiemsin Co-I (0.3 FTE)*	*11*	*45*	*11*	67
Civil Servant Salary: *Chris Wohl Co-I (0.2 FTE)*	*8*	*30*	*8*	46
Total Civil Servant Travel		*3*	*3*	6
In-house Procurement - *Materials*	*5*	*12*	*4*	21
External Procurement - *Virginia Tech*	*15*	*58*	*15*	88
External Procurement - *NIA (post-doc)*	*0*	*110*	*28*	138
Budget Total	45	280	75	400

Cost Sharing, non-NASA Partner Provided Budget ($K)	**FY12**	**FY13**	**FY14**	**TOTAL**
Virginia Tech	*3*	*13.1*	*3*	19.1
Total	3	13.1	3	19.1

Future Plans I

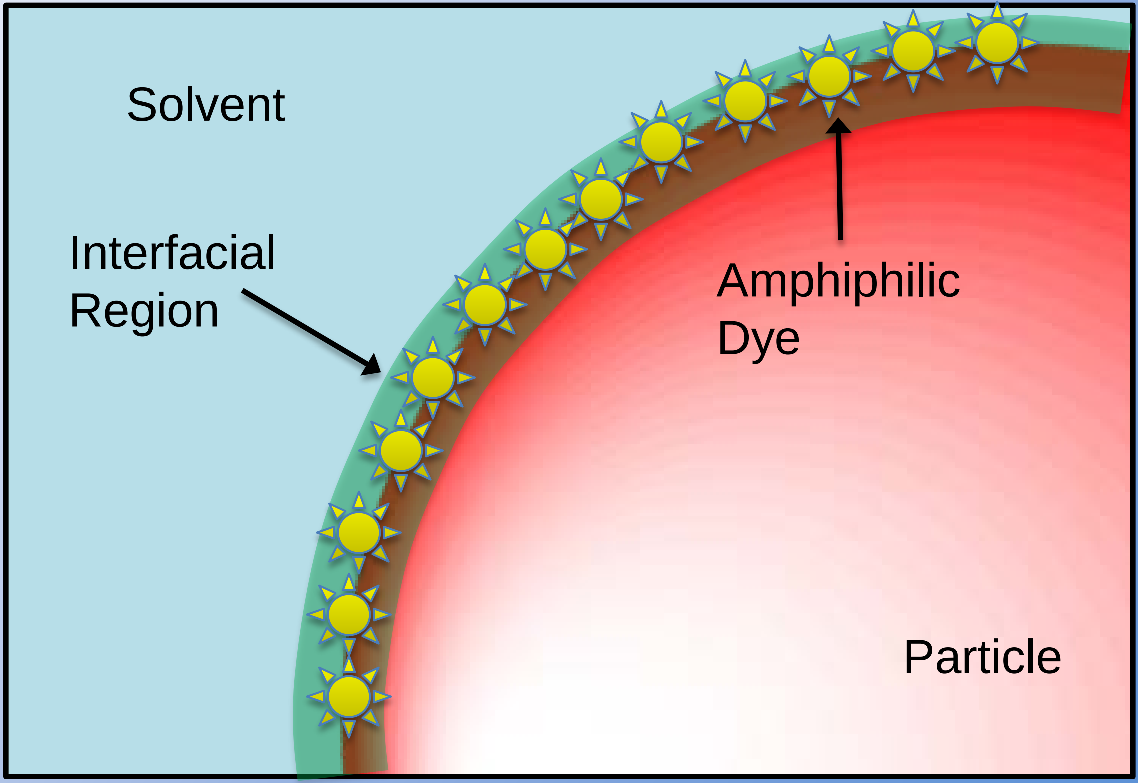
- Continue to work with current/existing dyes
  - Rhodamine B: develop water seeder?
  - Fluorescein: try different variants
- Explore additional existing dyes
  - Literature search turned up good options to try
  - Additional literature search for existing dyes that are not commercially available
- Continue to develop measurement instrumentation for T, P, LDV or PIV demonstrations: apply to supersonic free jet

Future Plans II

- Amphiphilic, chemically reactive dye

(Grk: both love; water-loving and fat-loving properties; surfactant)

- Design of a dye molecule to thermodynamically populate the interfacial region
- Functionalize the dye to chemically react with the styrene monomers
- Result:
  - Lower Loading
  - Reduced chance for leaching
  - Greater sensitivity to environmental temperature, pressure, etc.



Future Plans (Phase II Proposal)

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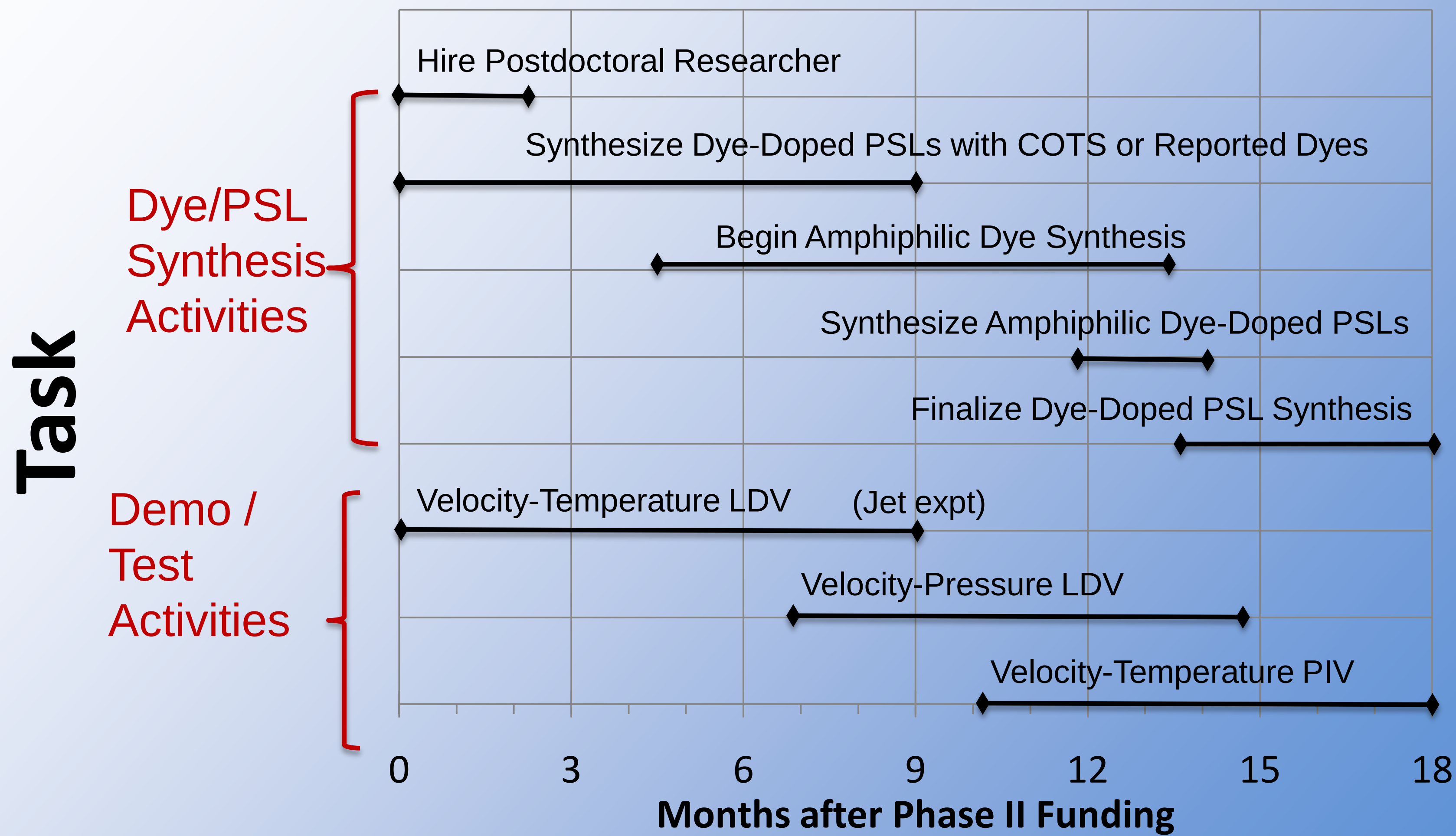

Conclusions

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- Developing new generation of particle-based instrumentation for wind tunnels
  - Temperature, Pressure, Concentration measurements to complement velocity and conventional instrumentation
  - Can use much of same equipment as LDV/PIV
- Have successfully doped Rh B dye into particles
  - Demonstrated temperature measurement at VT
  - Rh B is slightly toxic
    - Can we find a way to safely use it?
    - Can we find other, safer options?
- Many options of other dyes to explore; may invent new dyes to meet requirements.

Phase I Results

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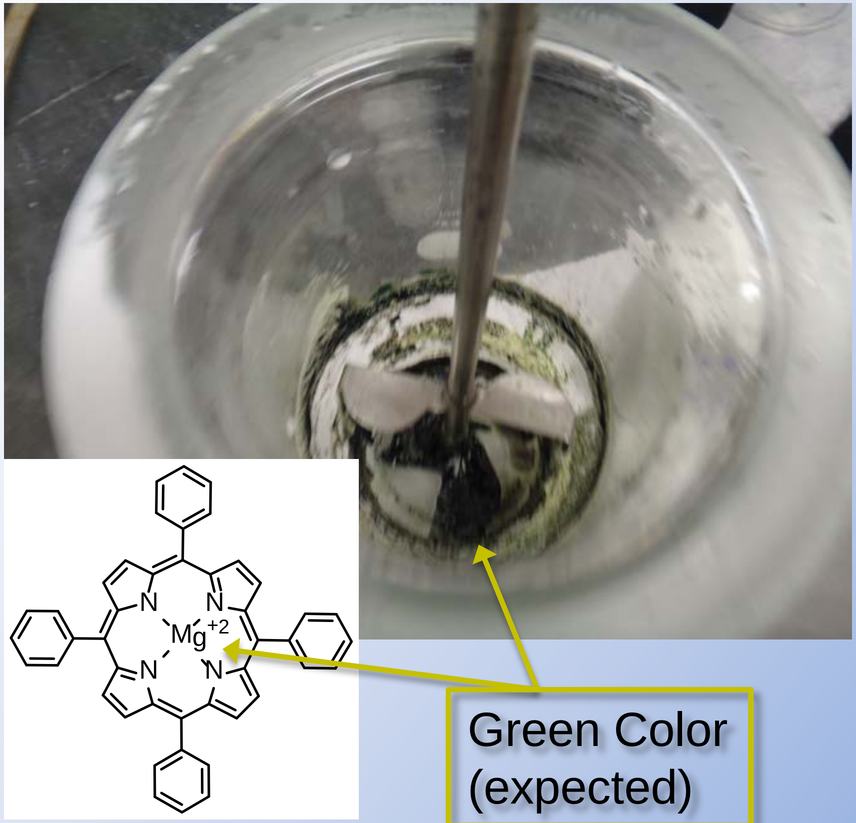
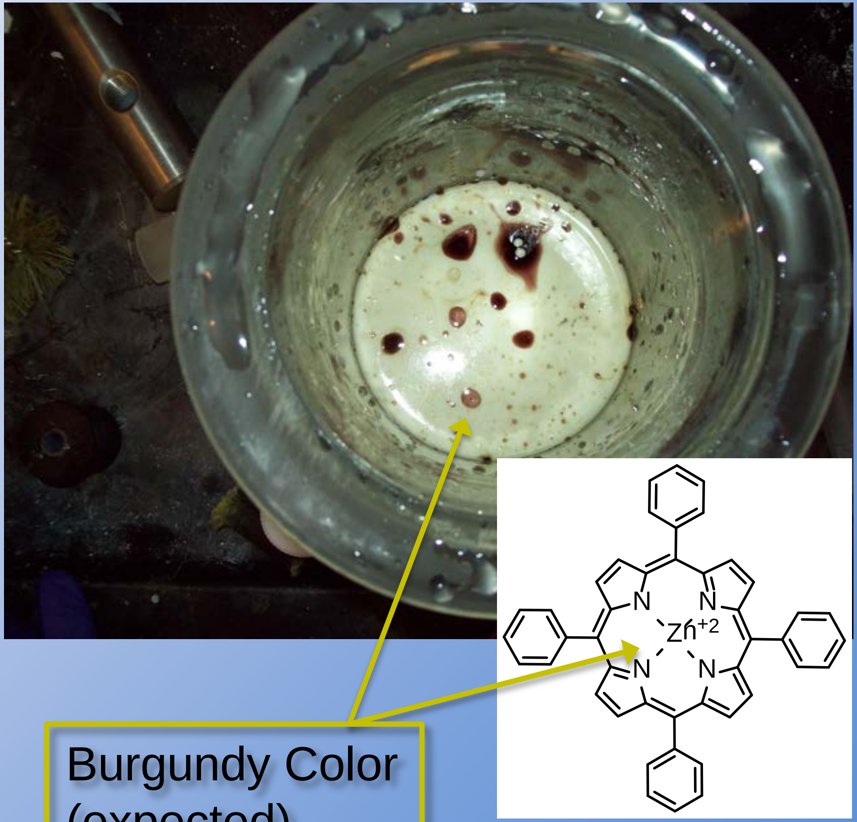
Synthesis with $MgSO_4$



Green Color (expected)

Synthesis with $ZnSO_4$



Burgundy Color (expected)

Phase I Results

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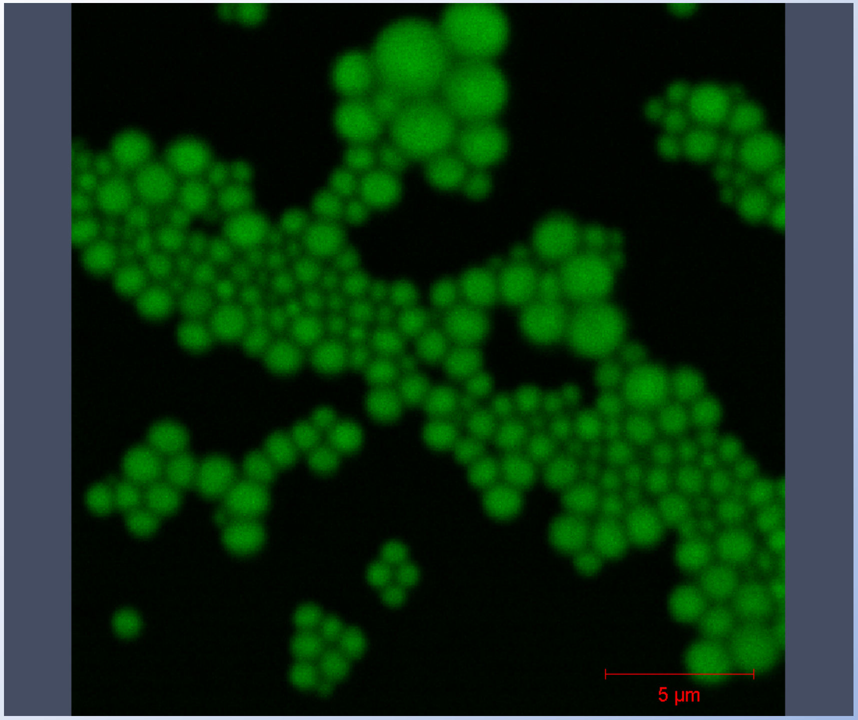
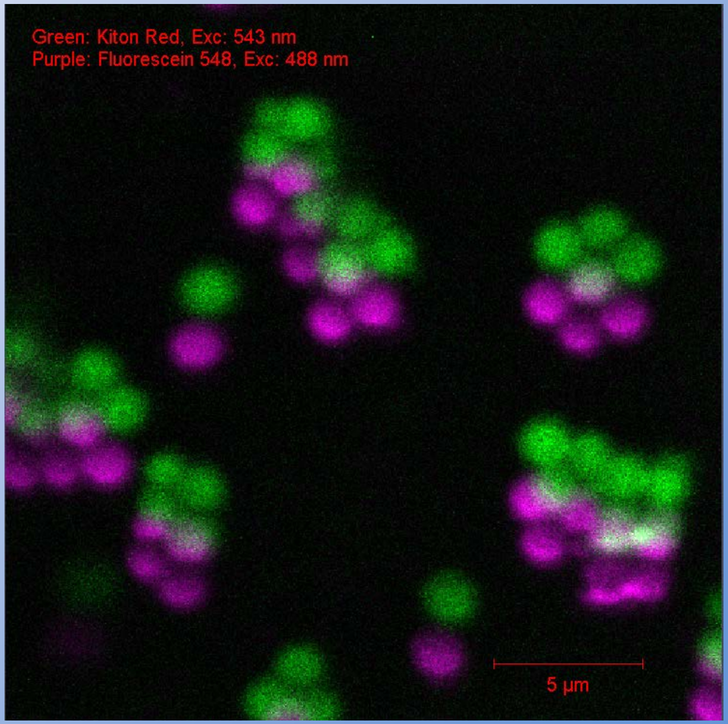
Rhodamine-doped PSLs



Fluorescein & Kiton Red-doped PSL



Fluorescent particle past work

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- **Literature Review:**
- Found no past work using doped PSL for thermometry
- Kimura et al. (2006) used PSLs painted with PSP to measure pressure.
- Fluorescein 27 is very attractive for temperature sensitivity, on the order of 3.5%/^{o}C (Dunand et al. 2010 and Sutton et al. 2008)
- Multiple dye techniques may offer significant advantages for improved sensitivity (Sutton et al. 2008).
- US Patent 4194877 claims invention of dye-doped PSLs.

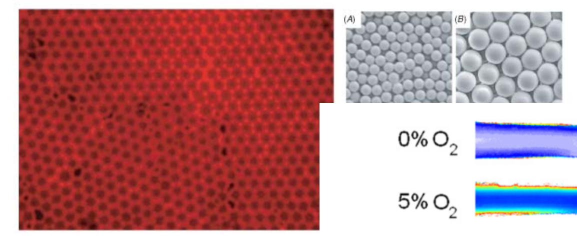

Figure 4. Left: phosphorescence microscopy images of PSBeads 3.0 μm ir SiOEP and PtOEP that were synthesized with different AIBN concentration

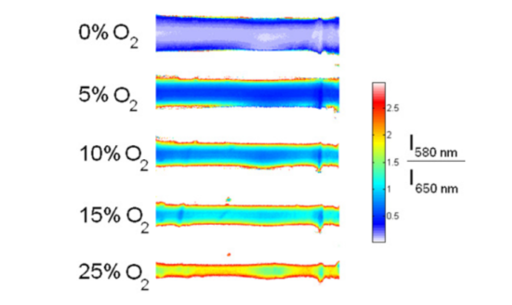

Figure 8. PSBeads ratio of $I_{580\ nm}/I_{650\ nm}$ images excited by a 400 nm laser in 0%, 5%, 10%, 15%, 25% and 30% oxygen concentrations.

Pressure sensitive PSLs and results of Kimura et al. (2006).

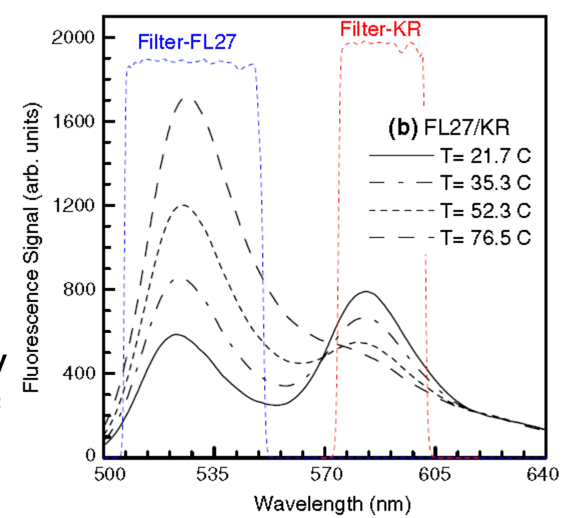

Fig. 12 Relative emission spectra of FL27/RhB mixtures (**a**) and FL27/KR mixtures (**b**) in water for temperatures ranging from 22 to 78°C. Also shown are the "filter masks" used for evaluating the ratiometric technique

Two-dye thermometry technique of Sutton et al. (2008).