Development of the Laser-Induced Incandescence Method for the Reliable Characterization of Diesel Particulate Emissions

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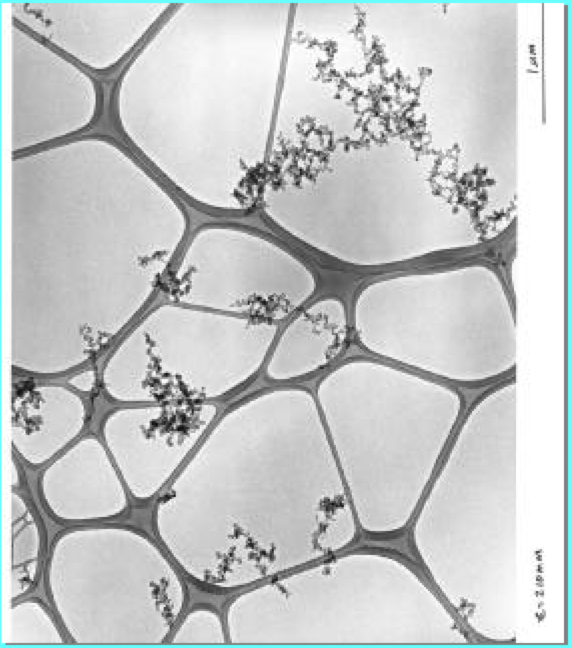
Outline

- Introduction
- Theory
- Results
  - diesel engine
  - direct injection gasoline automobile
  - transient measurements
- Summary

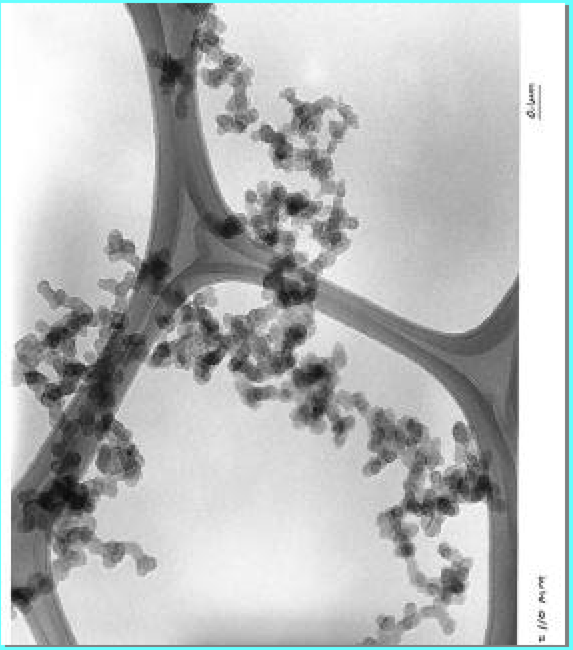
Diesel Particulates

- Concern about urban air quality/health:
  - further reductions in diesel PM regulations
  - **1988 - 0.6 g/bhp-hr, 2000 - 0.1 g/bhp-hr, 2007 – 0.01 g/bhp-hr**
  - extension to other vehicle/engine types
- Diesel engines are producing ***lower quantities of PM at smaller sizes***, nearing the sensitivity and reproducibility limits of the gravimetric technique

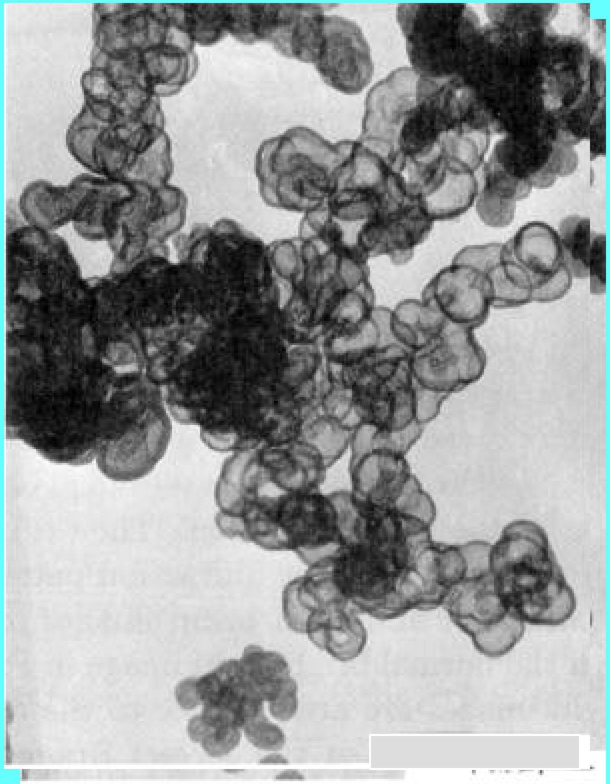
Transmission Electron Microscope (TEM) Images of Soot



1.0 mm



0.1 mm



Morphology

- nearly-spherical primary particles 20 –50 nm in diameter
- cluster into chain-like aggregates
- SOF absorbed onto the surface of the primary particles

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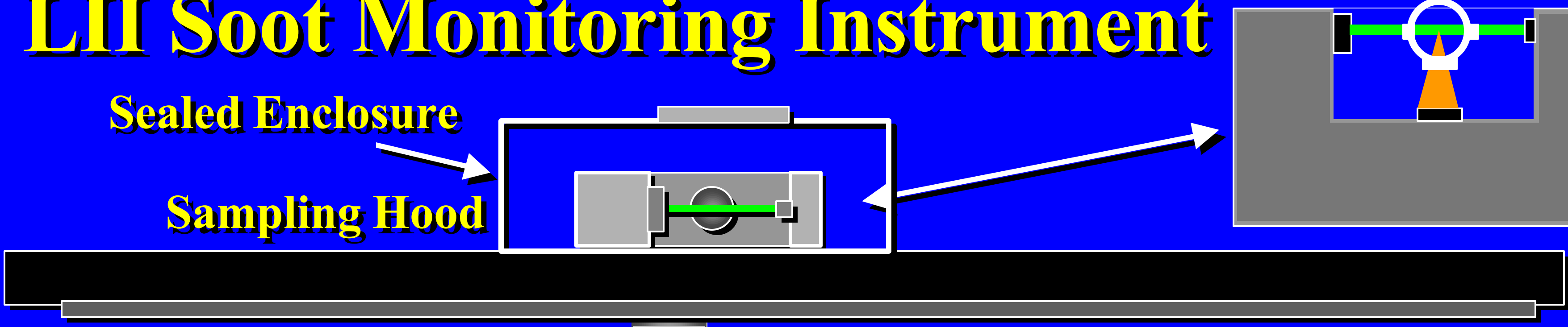
LII Soot Monitoring Instrument



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cooperating to

Develop, Evaluate, and

Commercialize

Laser-Induced Incandescence (LII)

Systems for Online Exhaust Particulate Material (PM) Monitoring

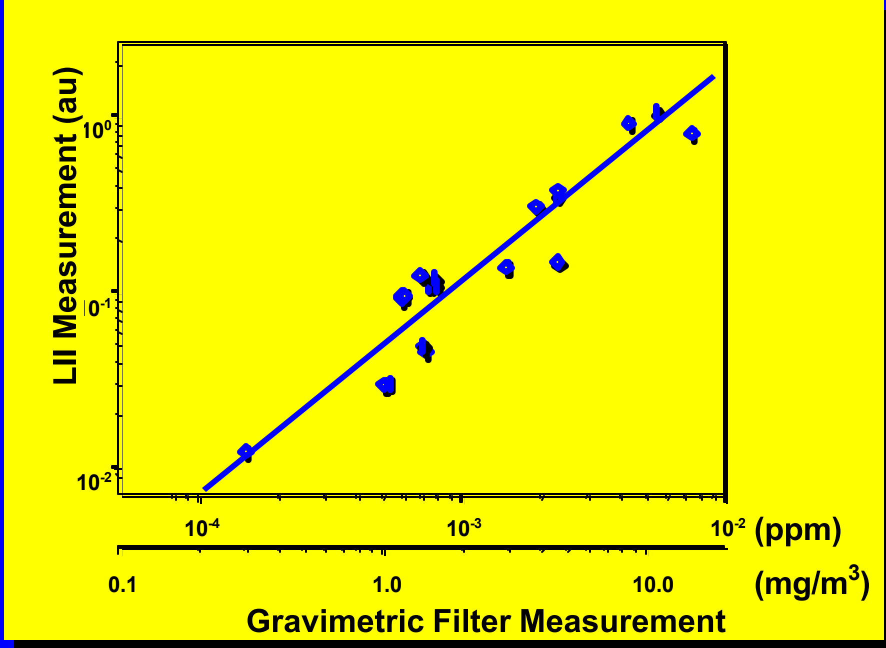
Other Mobile PM Sources

Laser-Induced Incandescence (LII) Features

- **In situ and Nonintrusive**
- **Spatially resolved**
- **Time resolved**
- **Large dynamic range**
- **Signal is proportional to particulate volume fraction**

Laser-Induced Incandescence (LII)

- We have demonstrated
  - the repeatability of LII measurements is far better than the repeatability of the standard gravimetric filter technique
  - LII measurements show good correlation with the filter mass measurements over a wide range of operating conditions and particulate levels



- Wider measurement range (10^6) and a much lower detection limit (ppt) make LII a potential standard instrument for PM measurements
- LII has a significant time advantage in collection and processing of data

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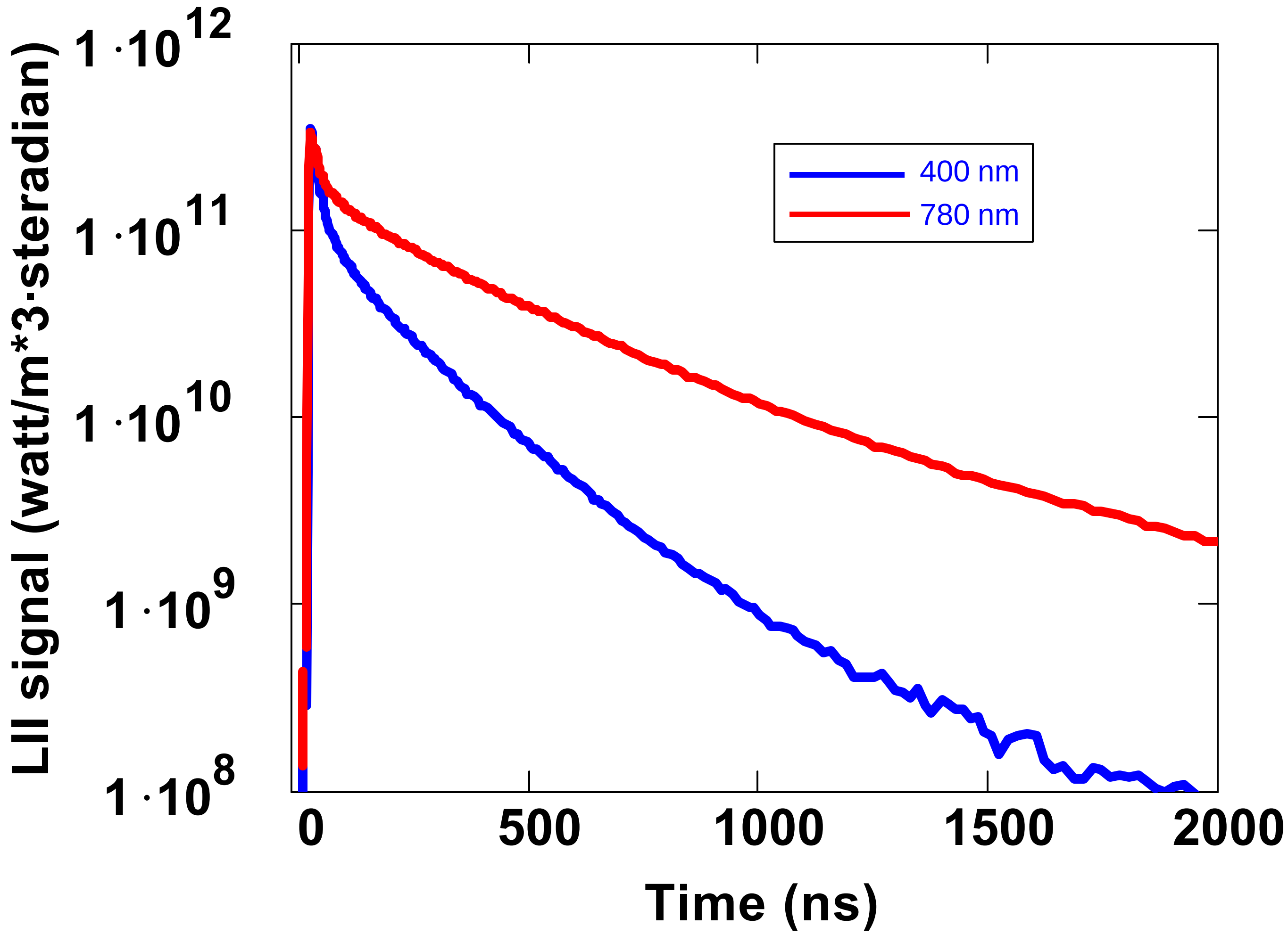
Laser-Induced Incandescence (LII) Concept

- **LII experimental approach:**
  - pulsed focused laser beam – Nd:YAG, 20 ns pulse
  - laser light produces rapid heating of PM to incandescence temperature
  - carbonaceous PM radiates incandescence as it cools to ambient temperature
  - incandescence signal is collected to determine PM concentration
- **LII theory**
  - a state-of-the-art numerical model of nanoscale (time and space) heat transfer to and from the particles

LII Signals at two wavelengths



Particulate Concentration

- Measure incandescence, I_λ, at two wavelengths and solve for temperature, T

$$\frac{I_{\lambda_1}}{I_{\lambda_2}} = \frac{\lambda_2^{\,6}}{\lambda_1^{\,6}} \frac{\left(e^{\frac{hc}{k\lambda_2 T}} - 1\right)}{\left(e^{\frac{hc}{k\lambda_1 T}} - 1\right)} \frac{E(m)_{\lambda_1}}{E(m)_{\lambda_2}}$$

- Use the temperature to determine the radiation from a single primary particle of diameter d_p

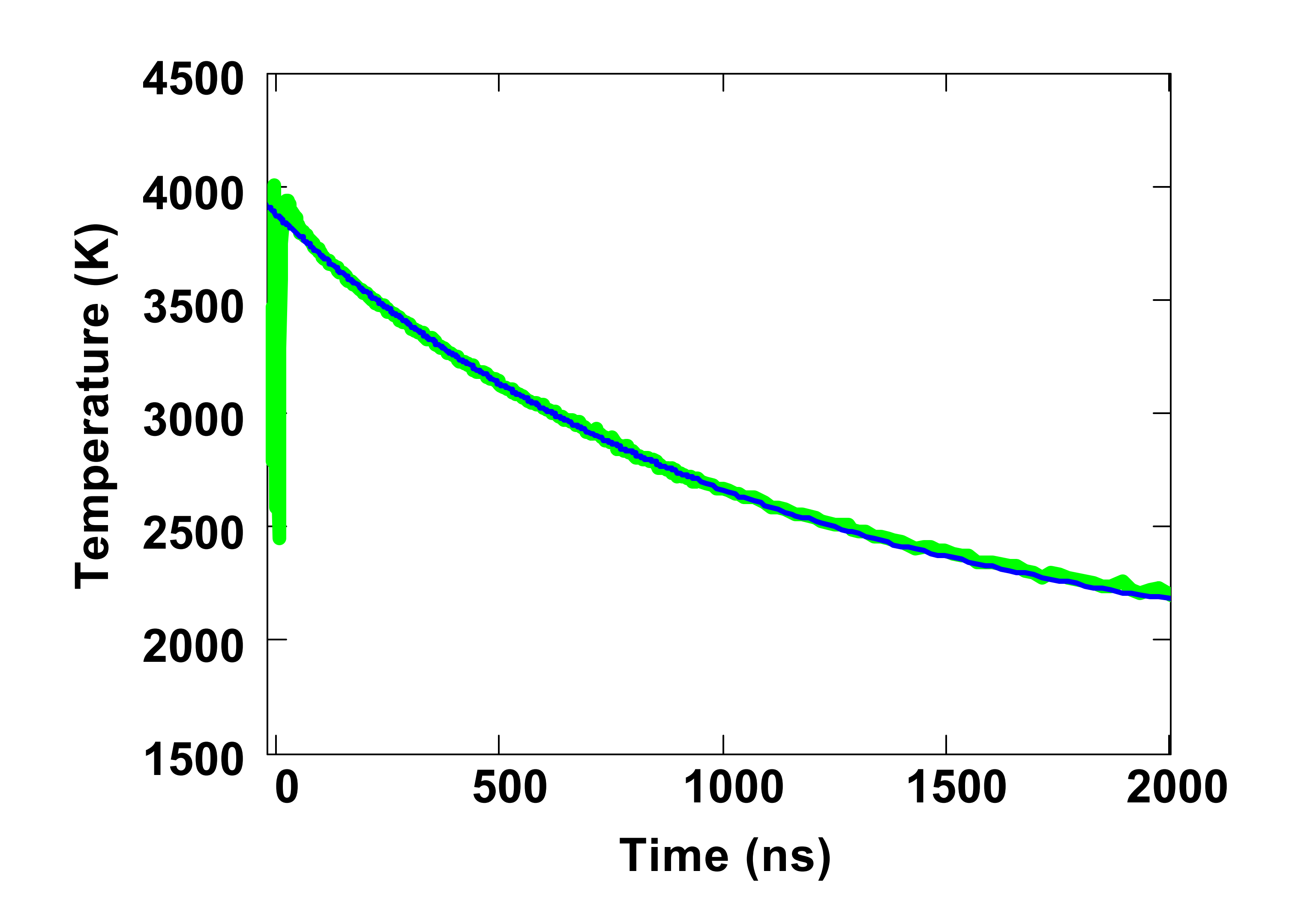
$$P_p(\lambda) = \frac{8\pi^3 c^2 h}{\lambda^6 \left(e^{\frac{hc}{k\lambda T}} - 1\right)} d_p^3 E(m)$$

Particulate Concentration

- **Number of primary particles, N_p, is then determined from the ratio of the experimental intensity to P_p**
- **Particulate volume fraction (PVF) is**

$$PVF = \frac{\mathbf{p}\ d_p^3}{6} \cdot \frac{N_p}{V}$$

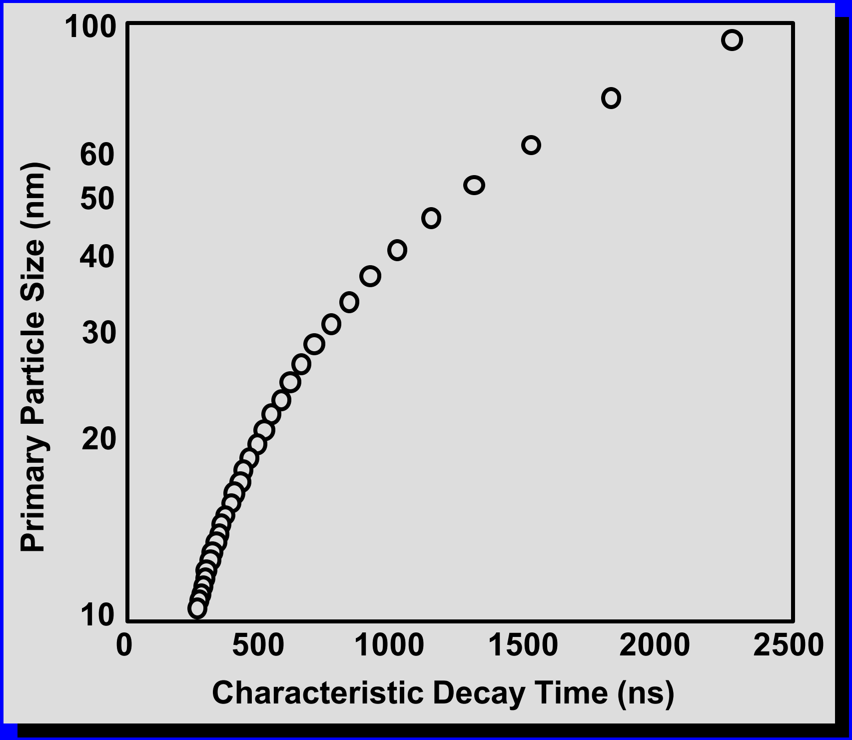
Temperature Decay Rate Related to Particle Size



Primary Particulate Size

- **Conduction phase**
  - –The temperature differential between the particle surface and the ambient gas decays steadily in an exponential manner

$$\Delta T = A \cdot e^{-\Delta t / t}$$



- **The primary particle diameter may be inferred *(McCoy and Cha, 1974)***

$$d_p = \frac{12 k_g a}{G\, l_{MFP}\, c_p\, r_p\, t}$$

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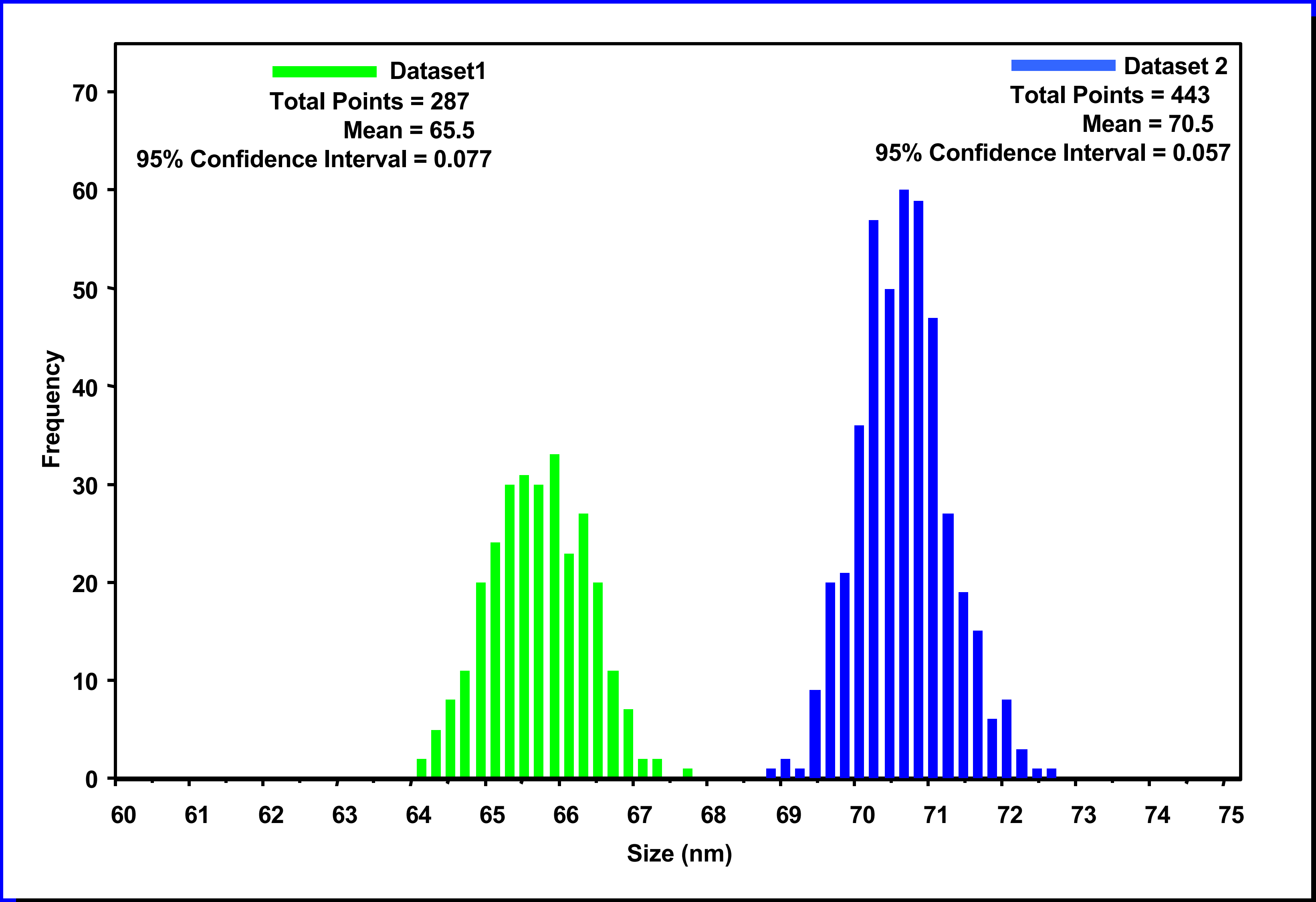
Soot Primary Particle Size at Two Combustion Conditions



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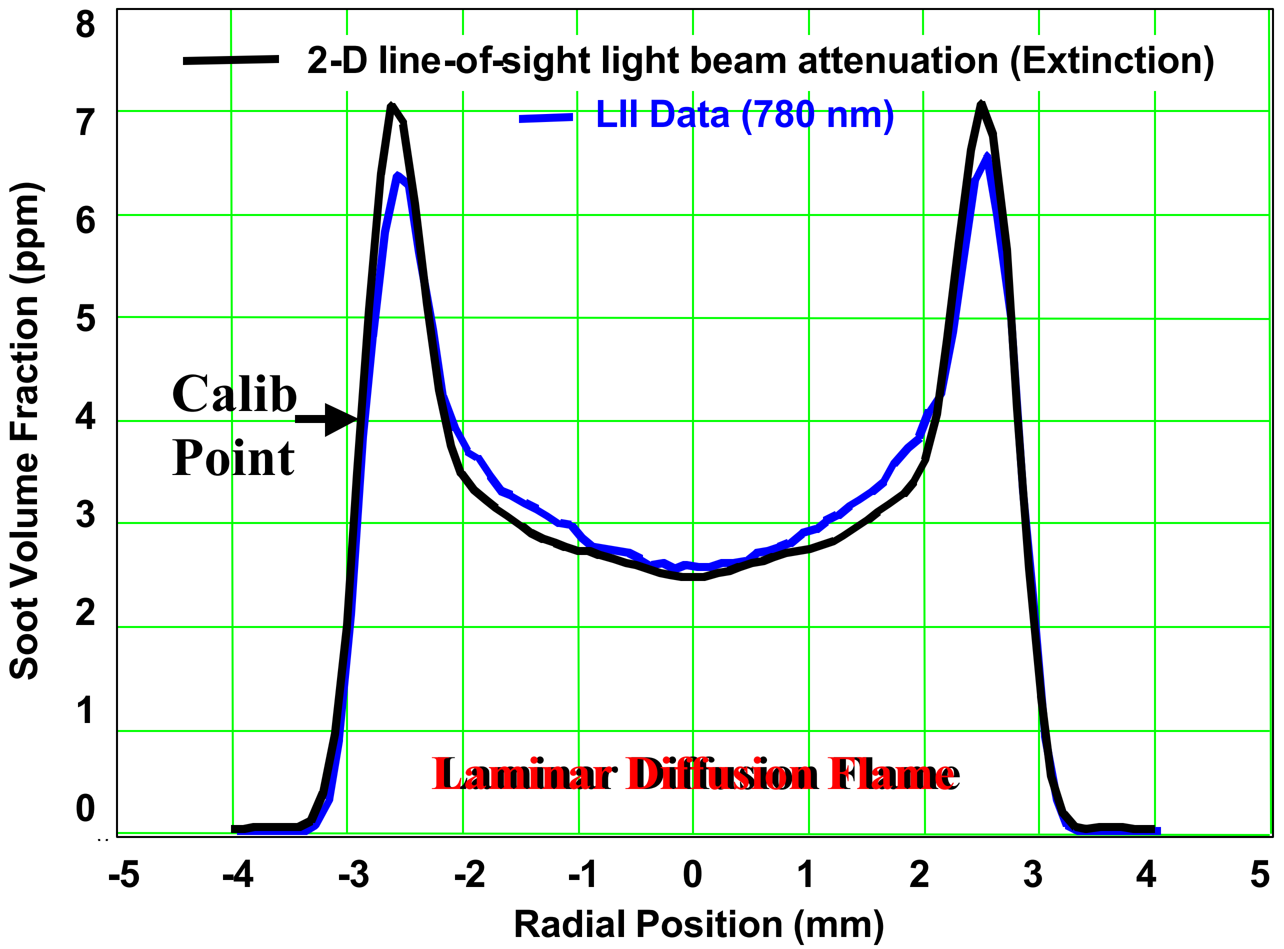
Conventional LII Calibration

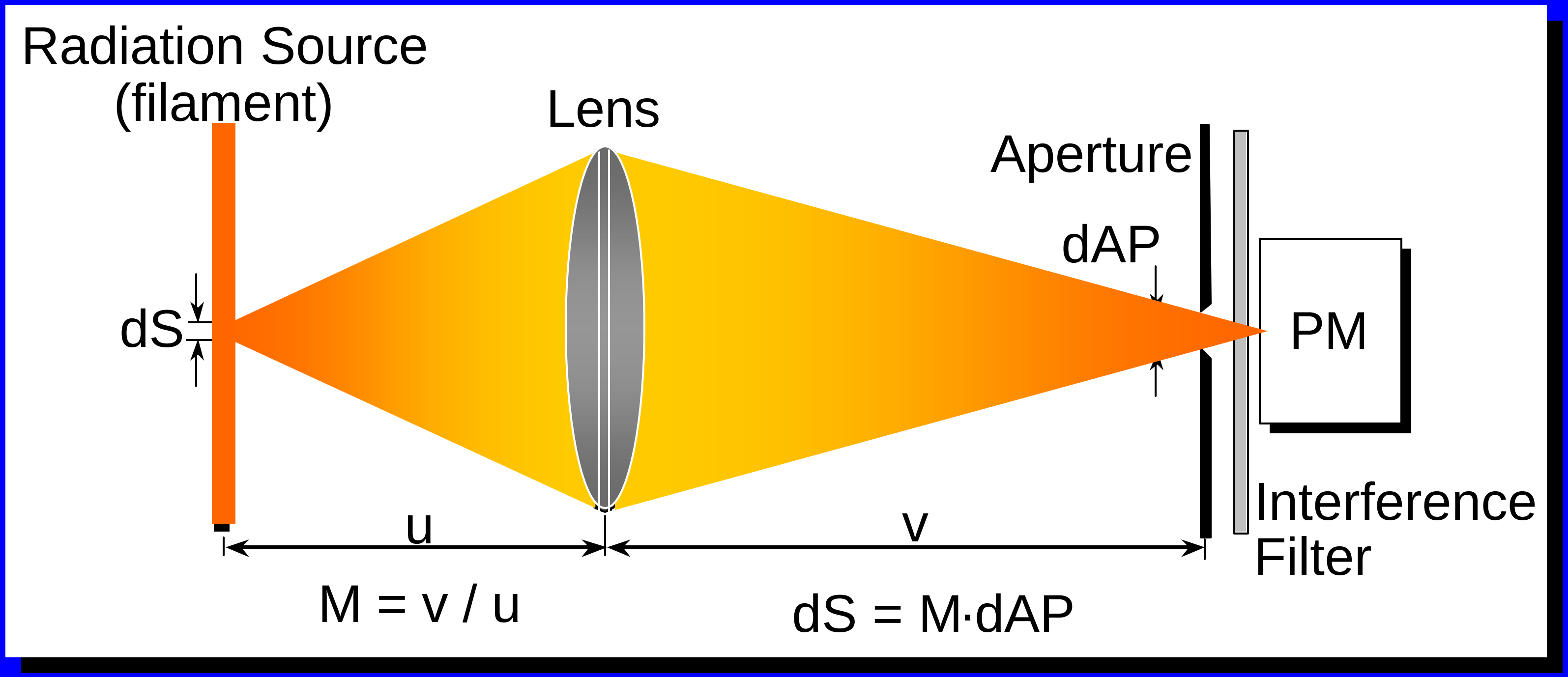


LII (780 nm)
2-D soot data

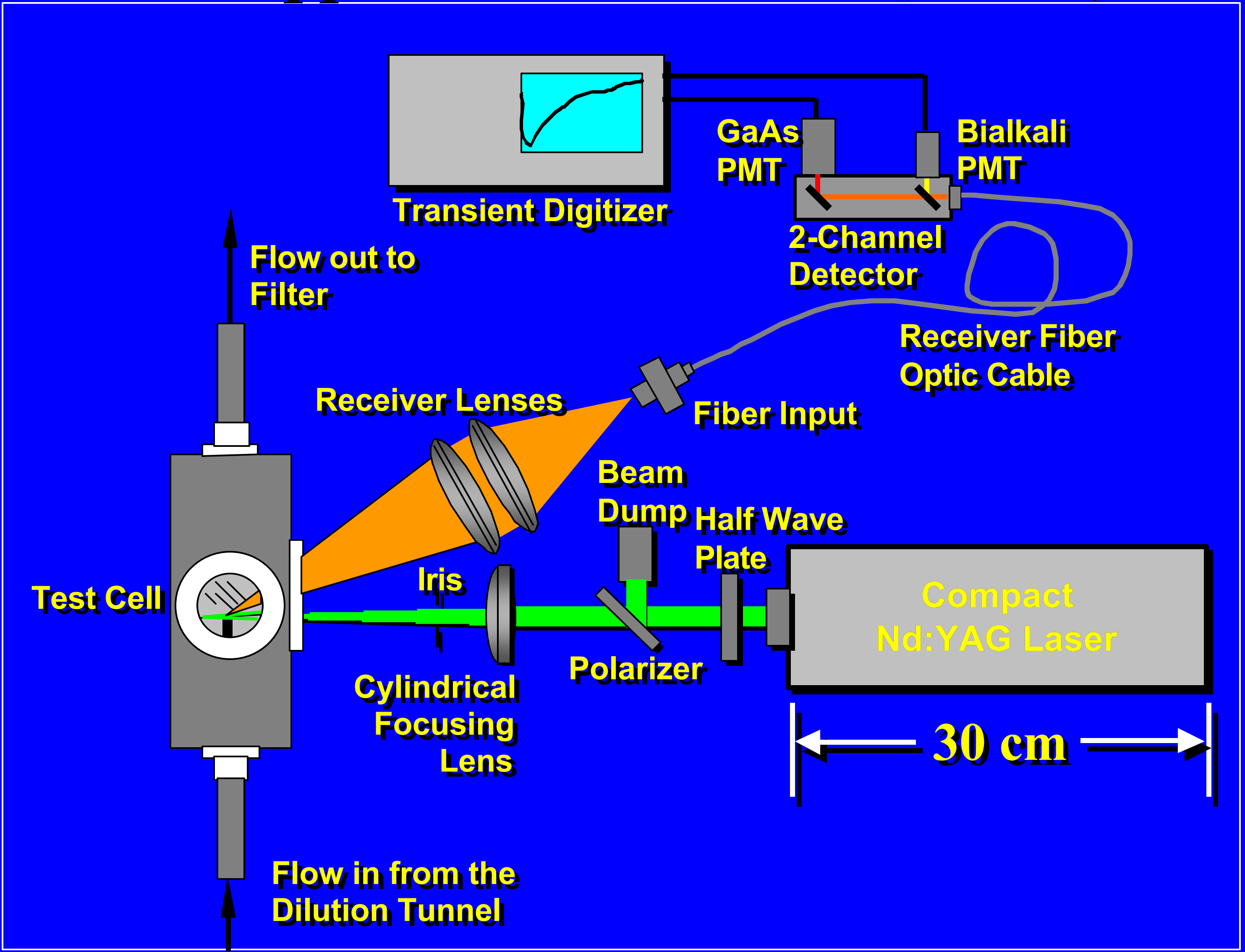
LII Calibration Using Absolute Light Intensity

- Single point calibration is made in a known source at a known temperature, which results in an absolute sensitivity (in $W/m^3 \cdot ster$) for the detection system
- Must account for losses through optical components (lenses, filters, fibers, windows, etc.) and the gain characteristics of the photodetectors
- Method can be automated and invisible to the user

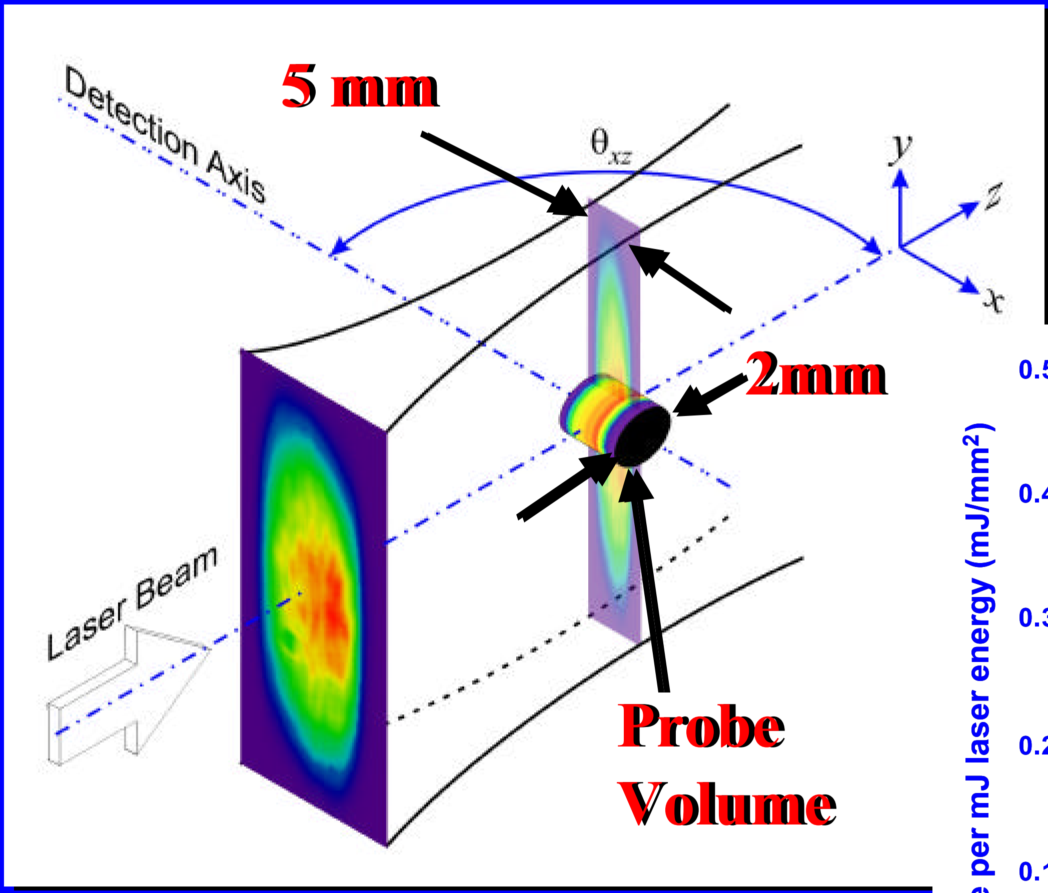
Absolute Intensity Calibration Concept



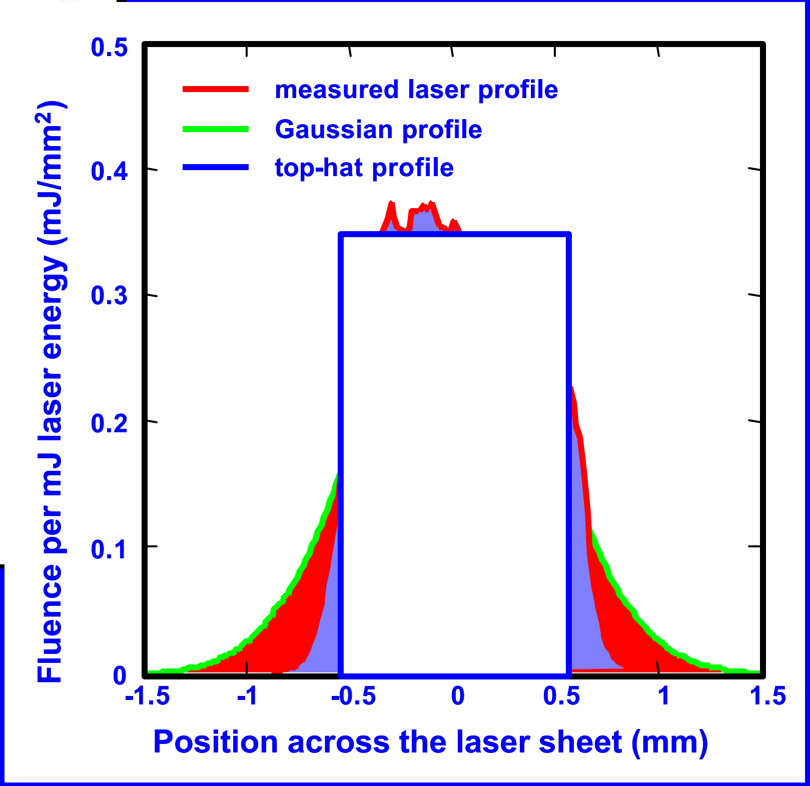
LII Apparatus Schematic (Diesel)



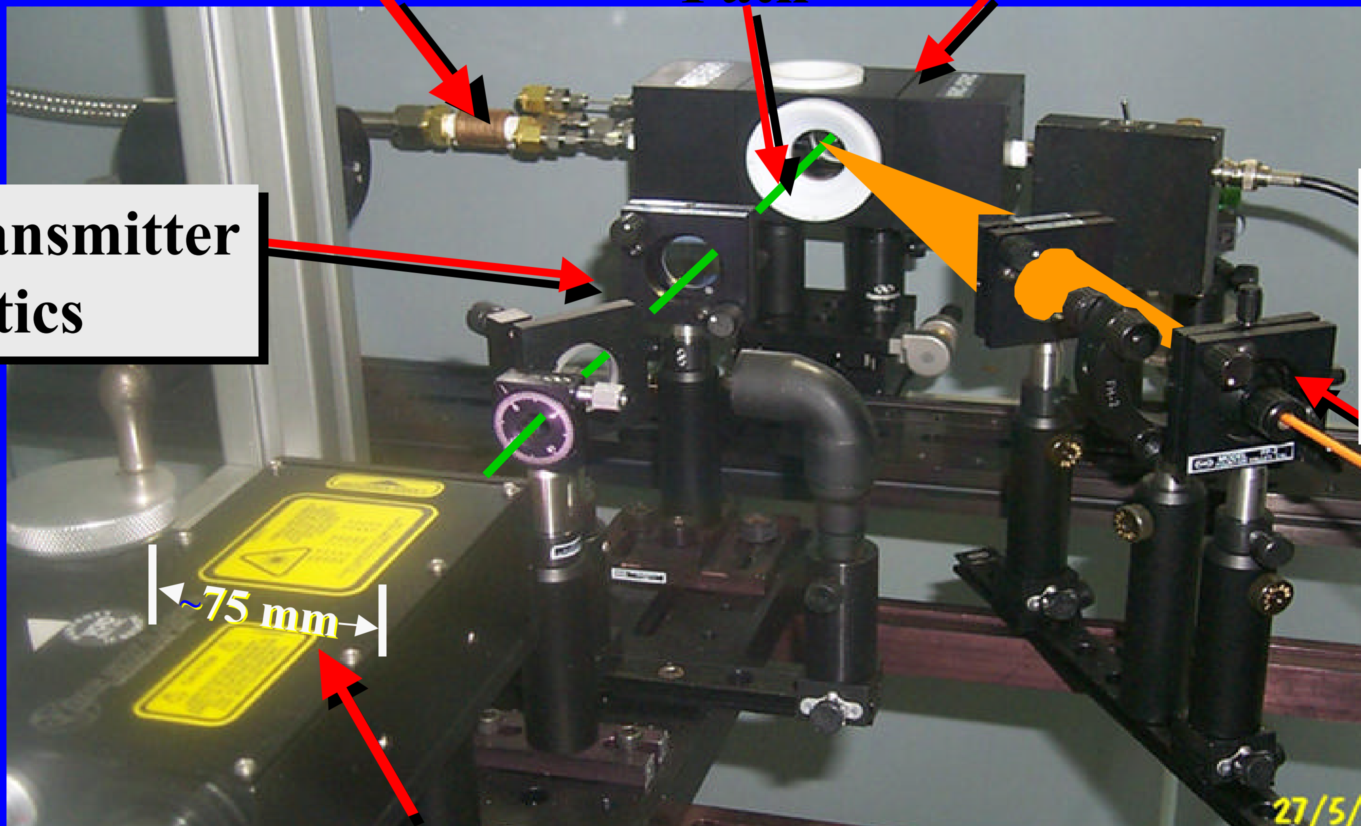
Laser Sheet and Sample Volume



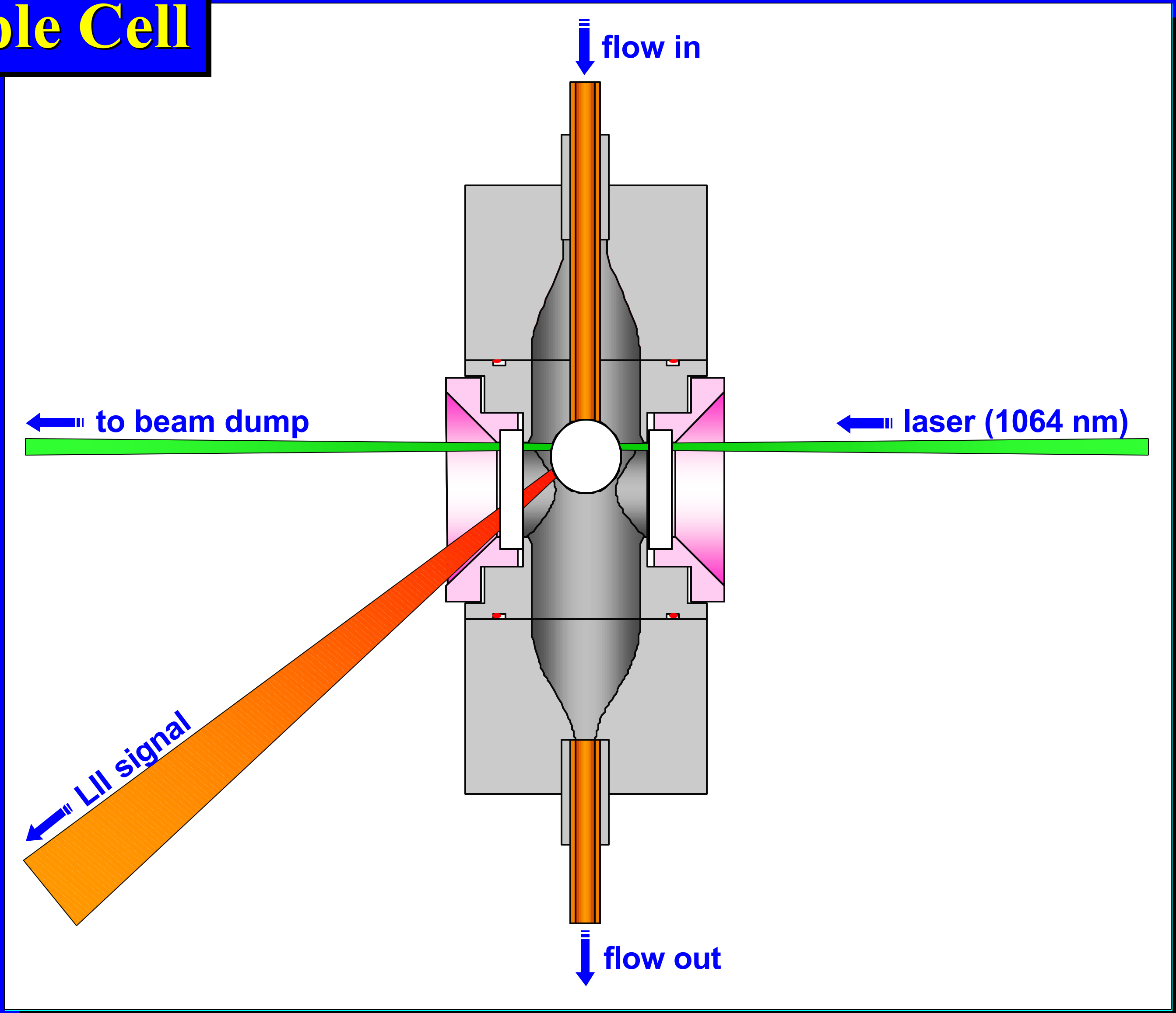
- Each fluence level will heat particles to a different temperature
- Ideal is a top-hat profile



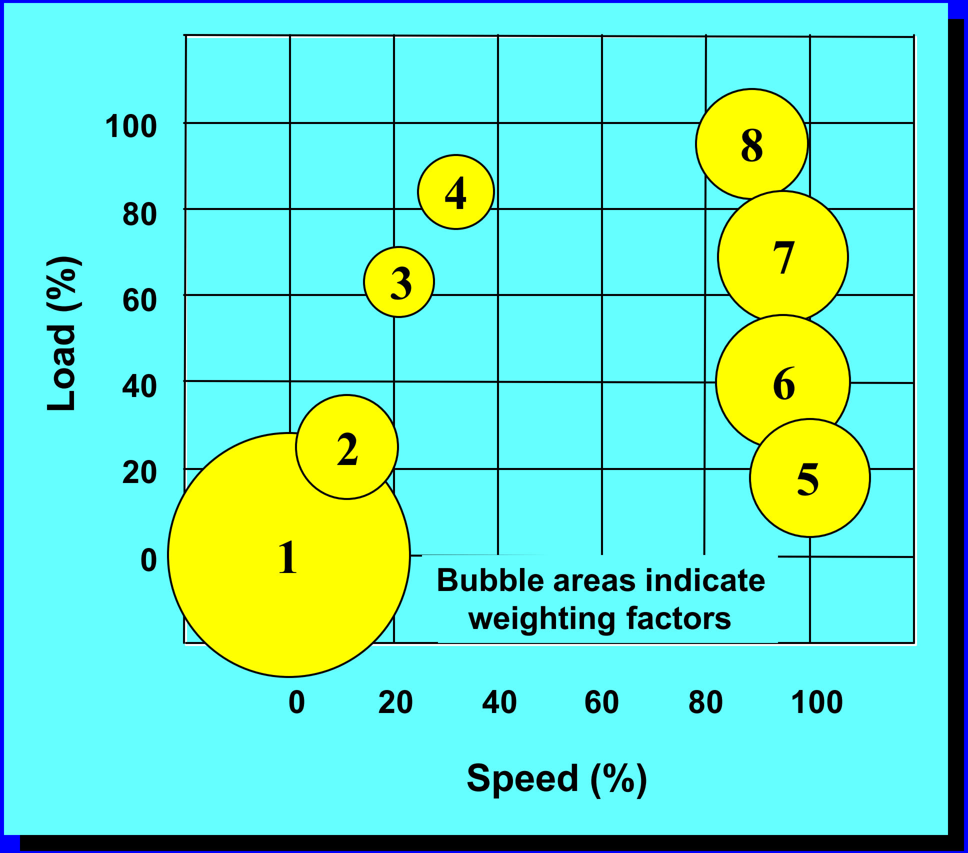
Photograph of the Compact LII System and the Test Cell



Sample Cell



AVL 8-Mode Steady-State Simulation



- Engine speed 600 to 1900 rpm
- Load 0 to 95%

$$BSE = \frac{\sum (Emission\ Rate)_i \times WF_i}{\sum (Brake\ Power)_i \times WF_i}$$

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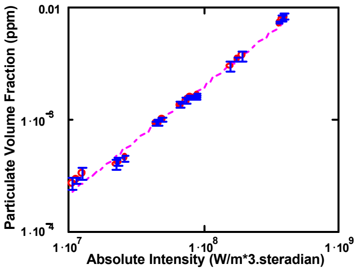
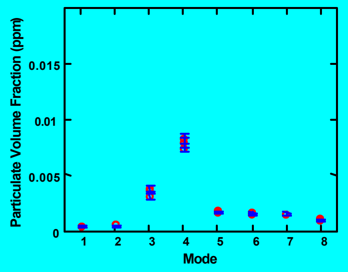
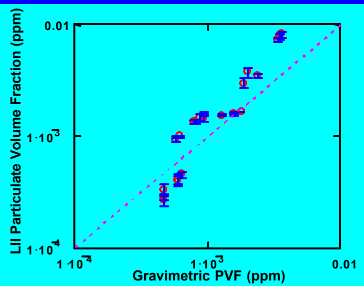
Diesel Particulate Concentration



Calibration

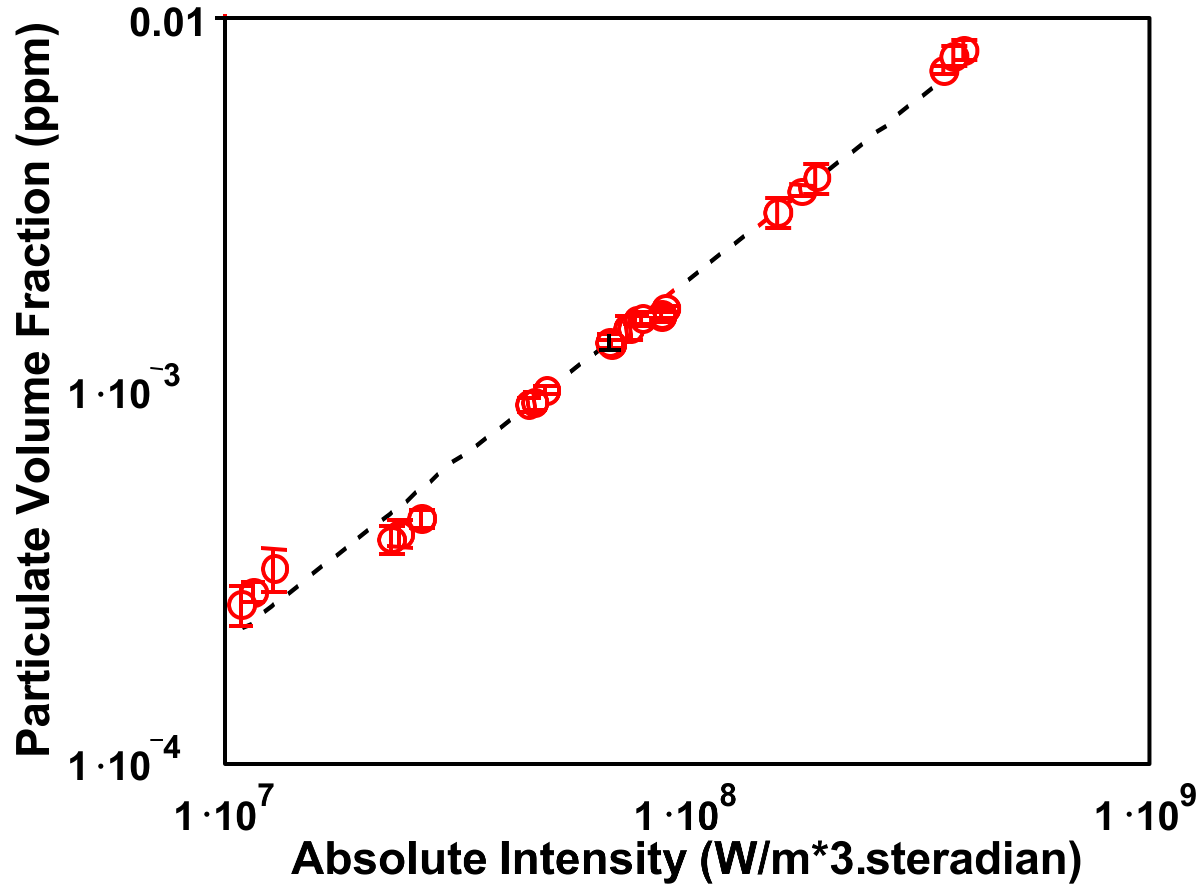


Mode-by-Mode



Comparison

AVL 8 – mode steady-state simulation



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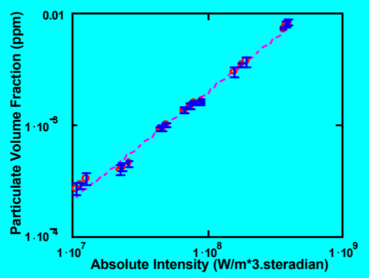
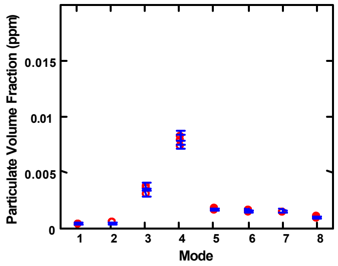
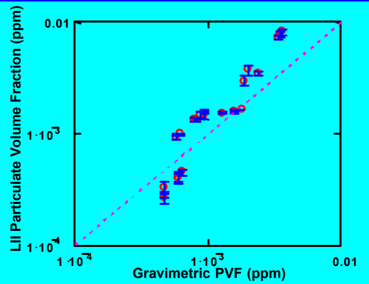
Diesel Particulate Concentration



Calibration



Mode-by-Mode



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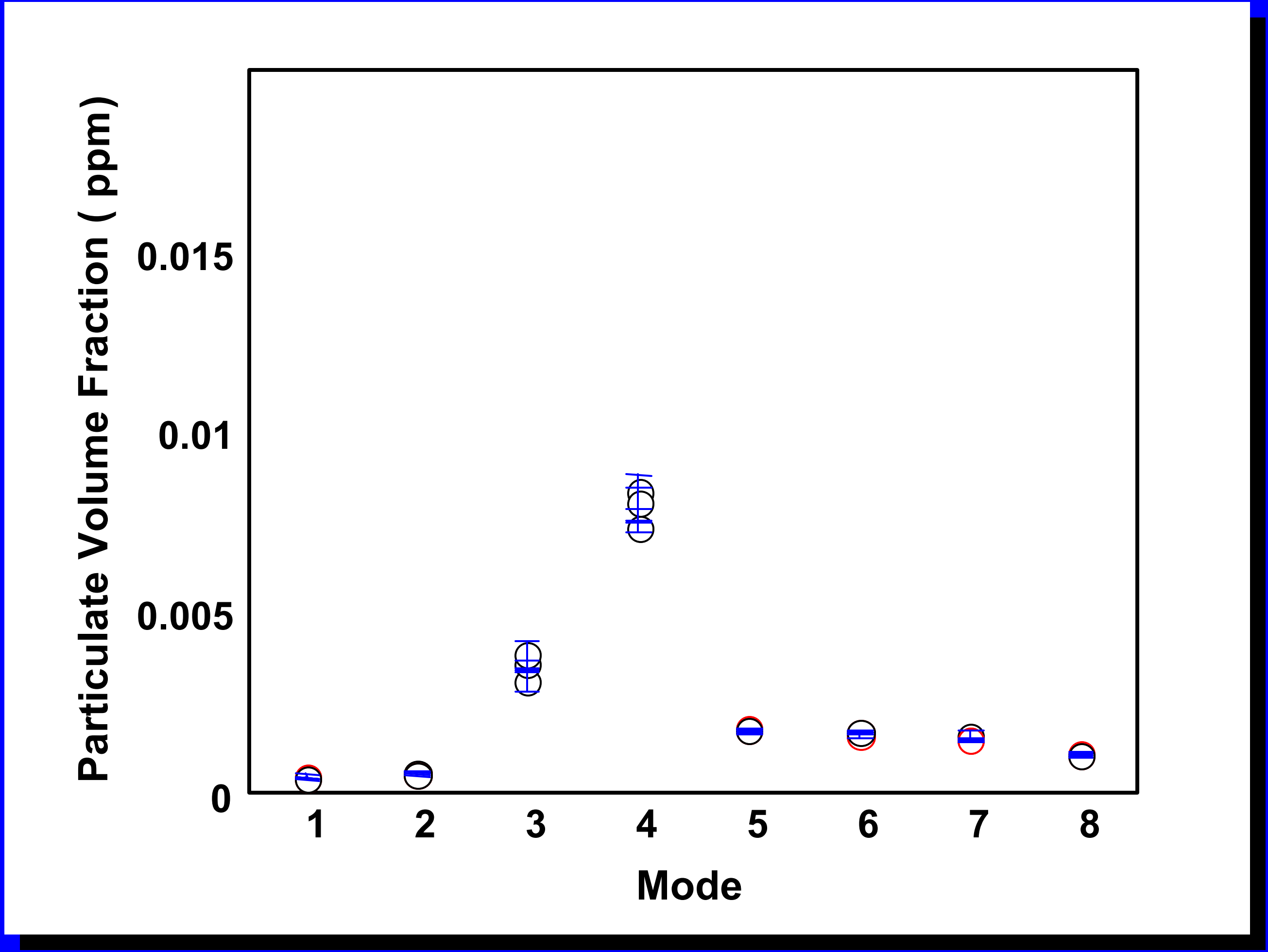

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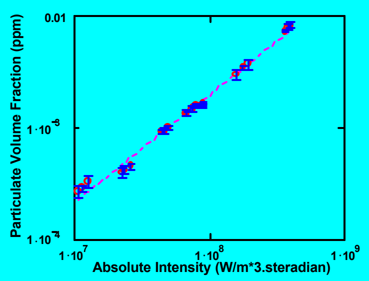
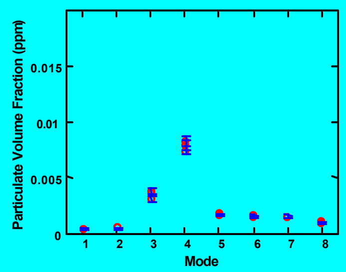
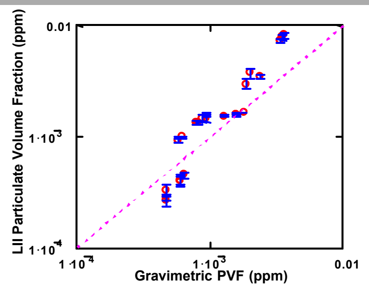
Diesel Particulate Concentration



Calibration

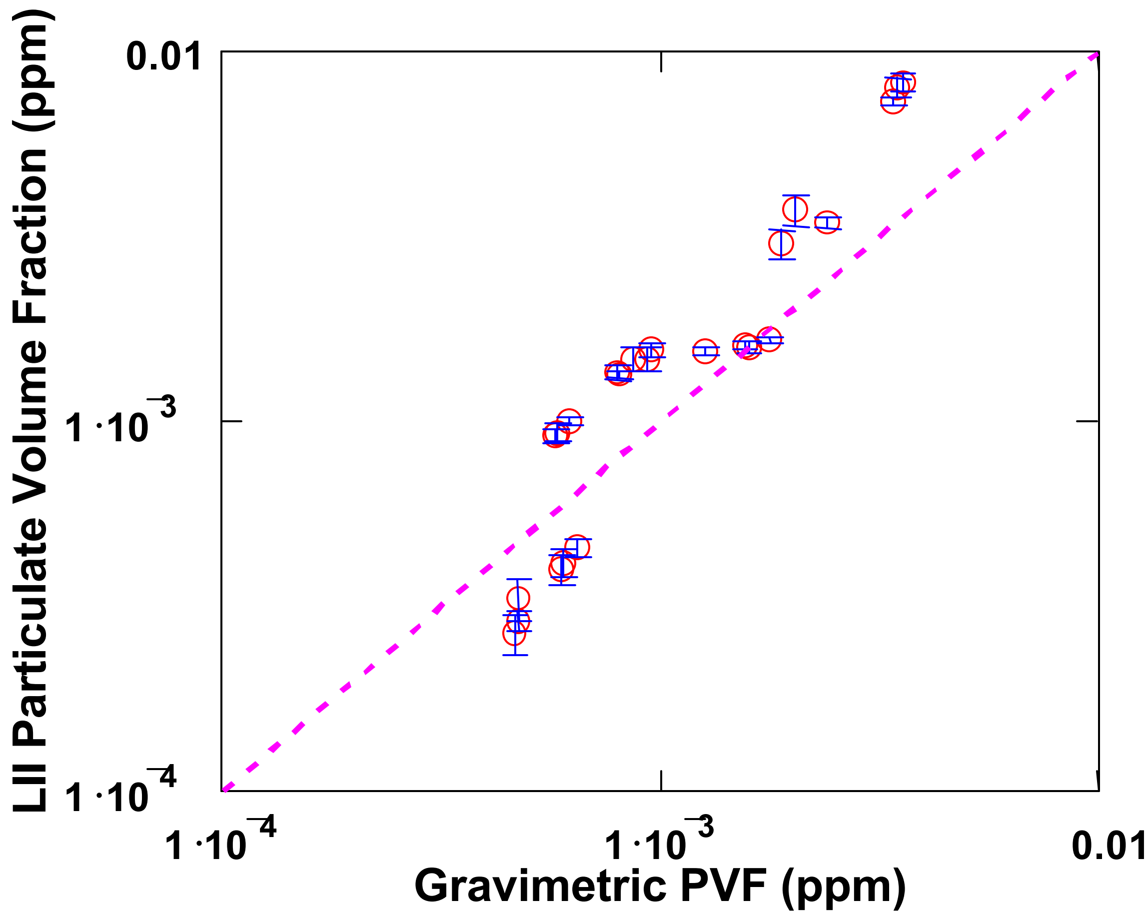


Mode-by-Mode



Comparison

AVL 8 – mode steady-state simulation



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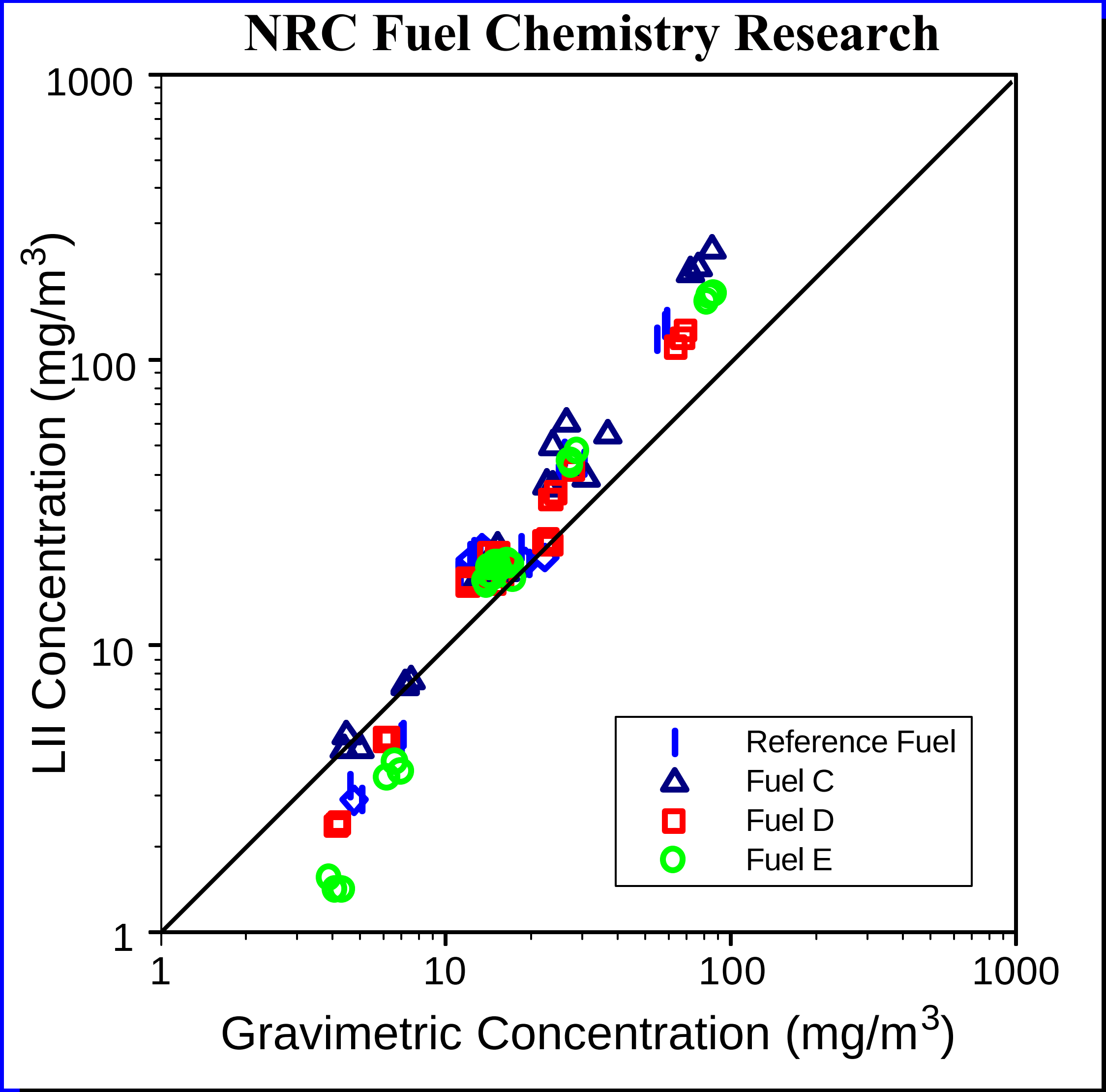
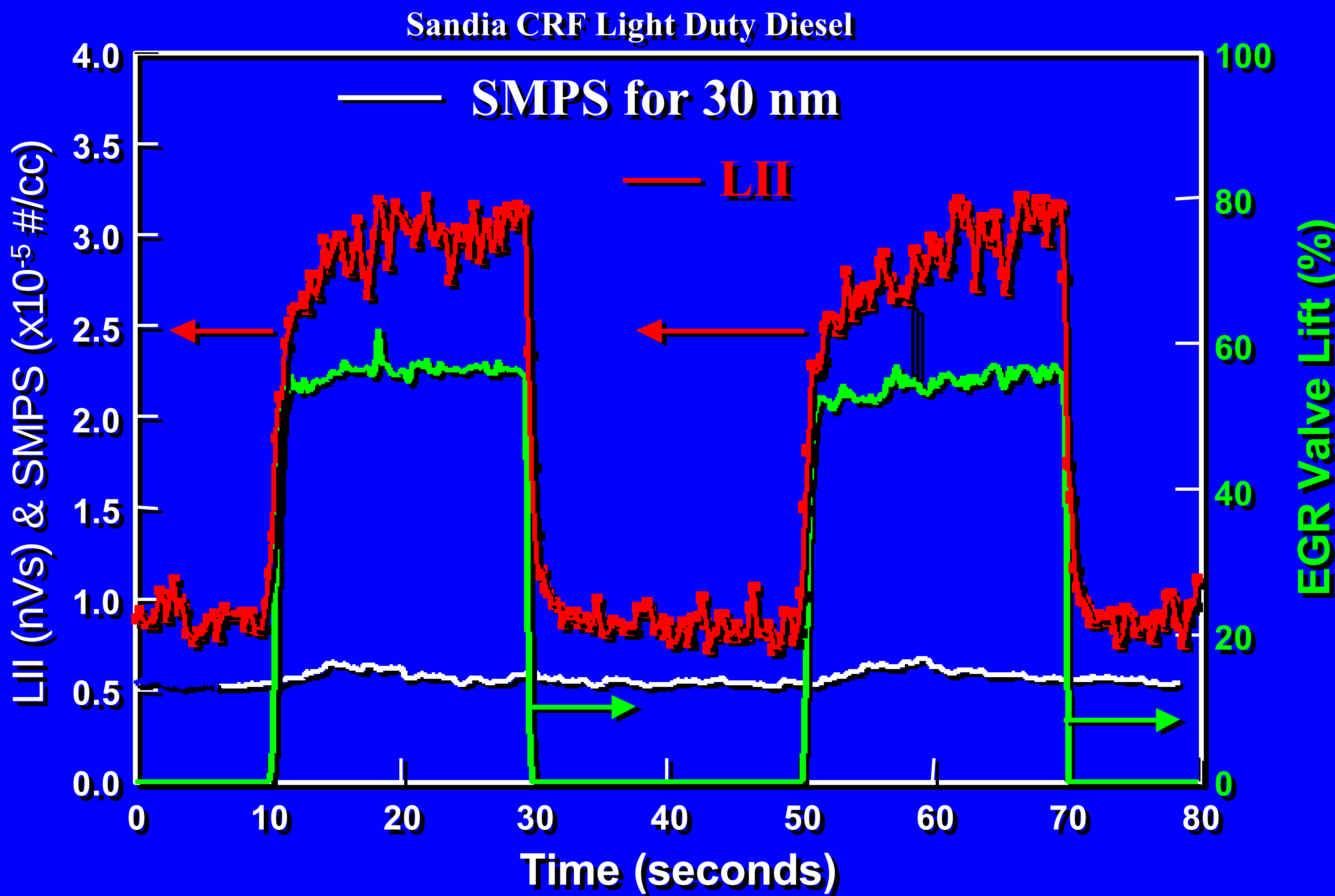
Diesel Summary: LII vs. Gravimetric



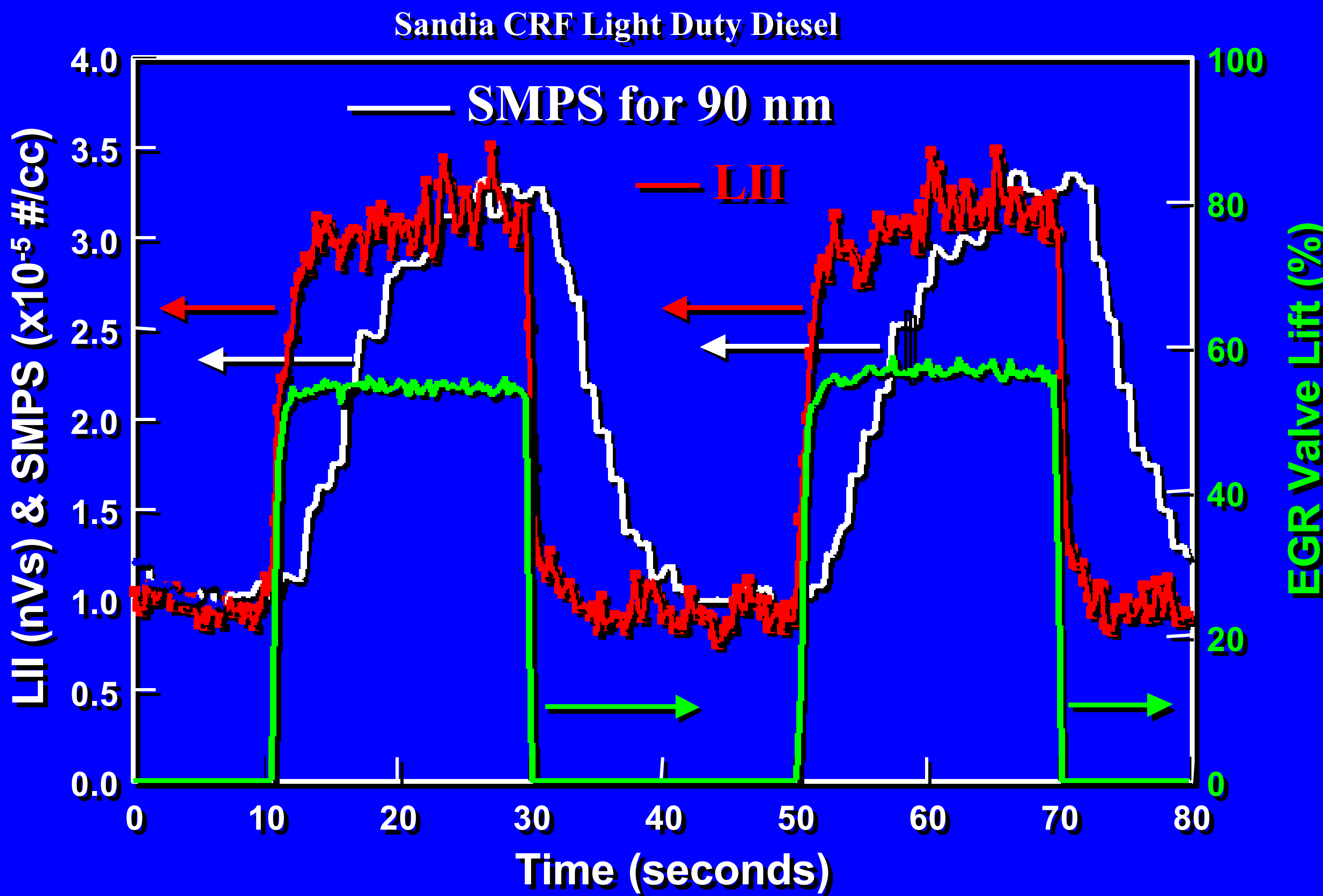
Particulate Concentration: Discussion

- Gravimetric sampling includes an organic fraction that does not contribute to the signal measured by LII
- Repeatability of our gravimetric data is poor compared to LII method
- The density of the particulates is required to convert the mass determined by the gravimetric filter method to a volume fraction for comparison with LII, and density used is for dry soot
- LII measurements could have been made in the exhaust manifold with 5 to 10 times higher signal levels

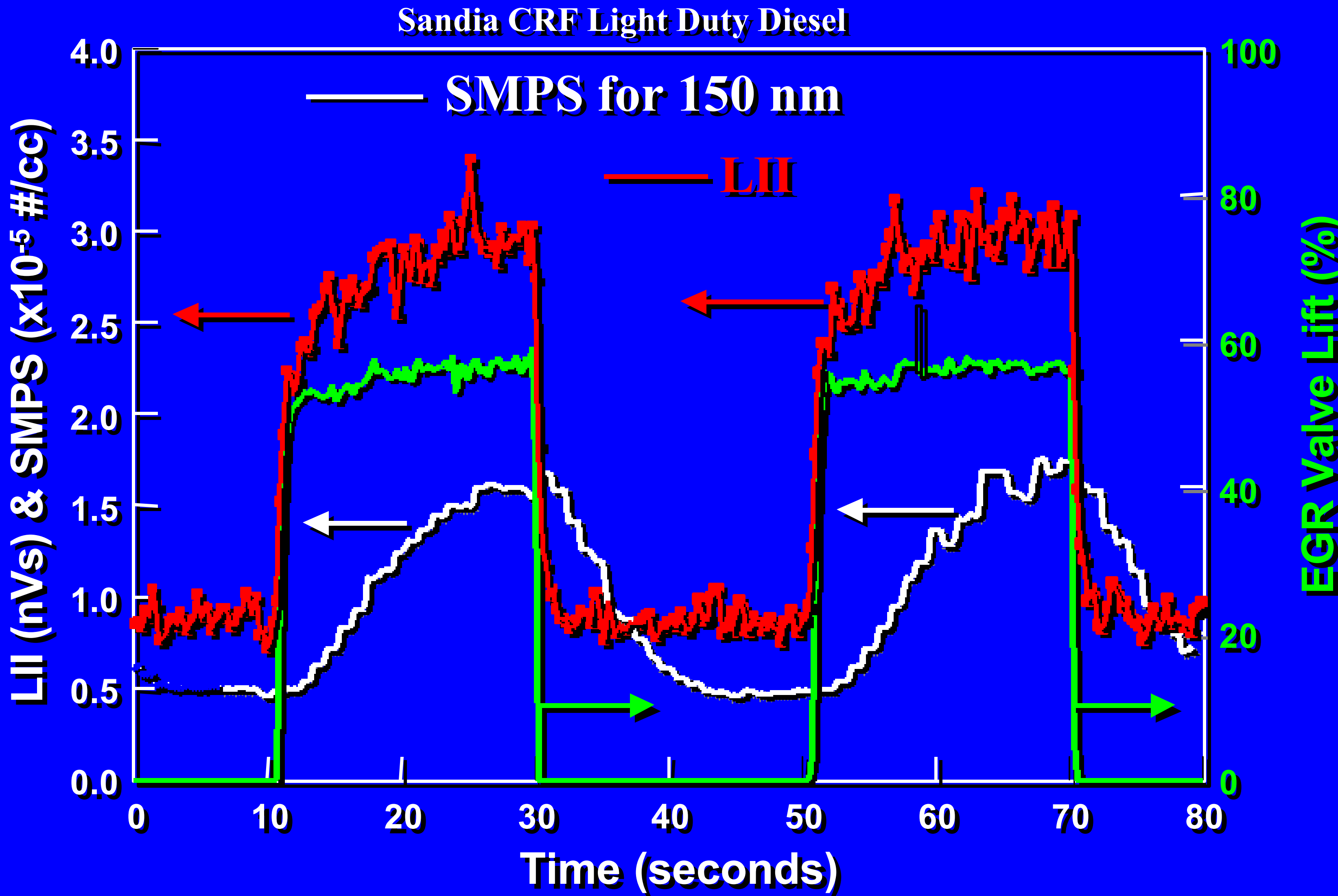
Throttle Transient 1200 rpm - LII (30 nm SMPS)



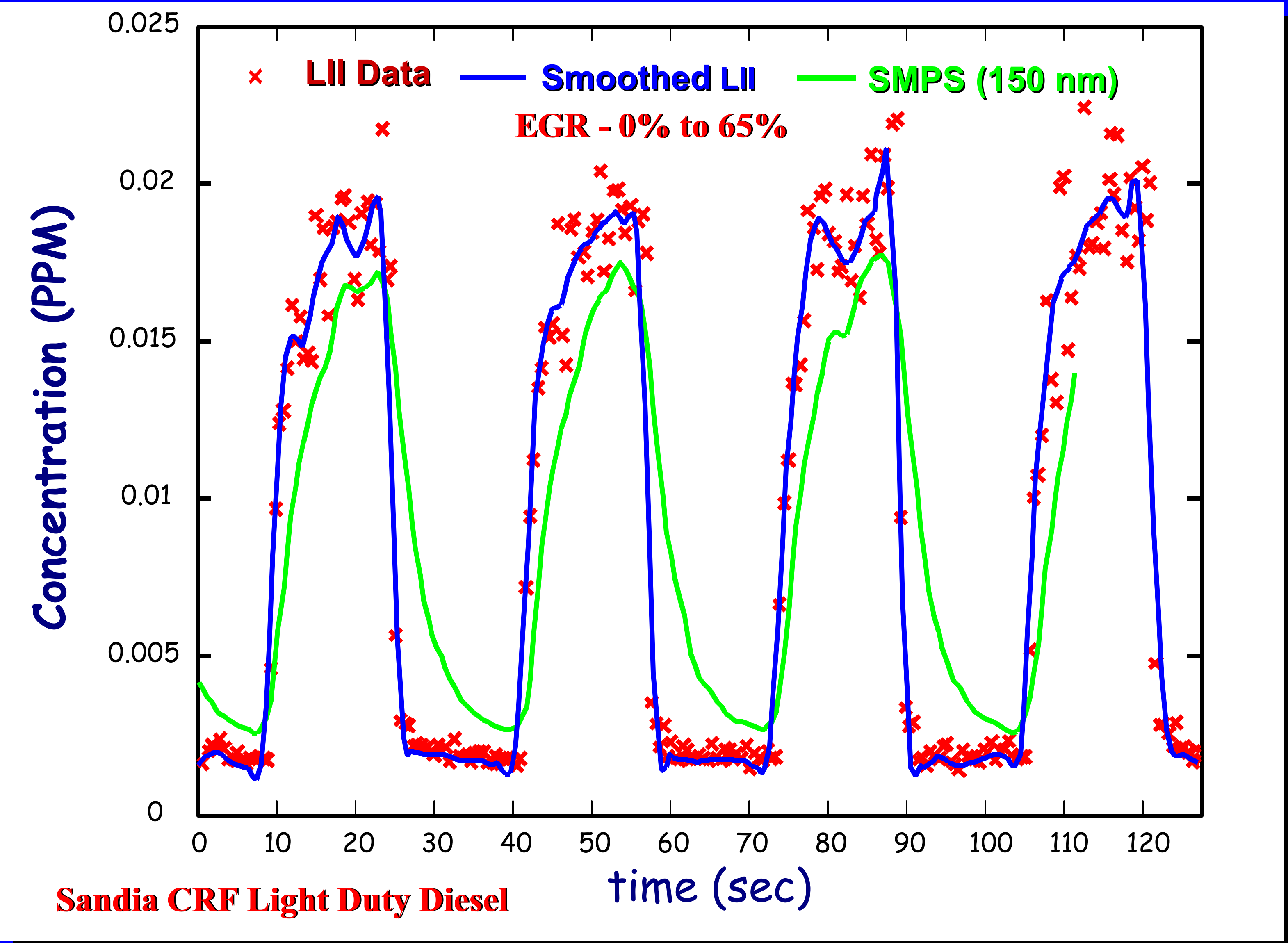
Throttle Transient 1200 rpm- LII (90nm SMPS)



Throttle Transient 1200 rpm - LII (150 nm SMPS)



EGR Transient (1500 RPM, throttle @ 25% max)



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Tailpipe Particulates Measurements (DISI)

SMPS

ELPI

LII Instrument

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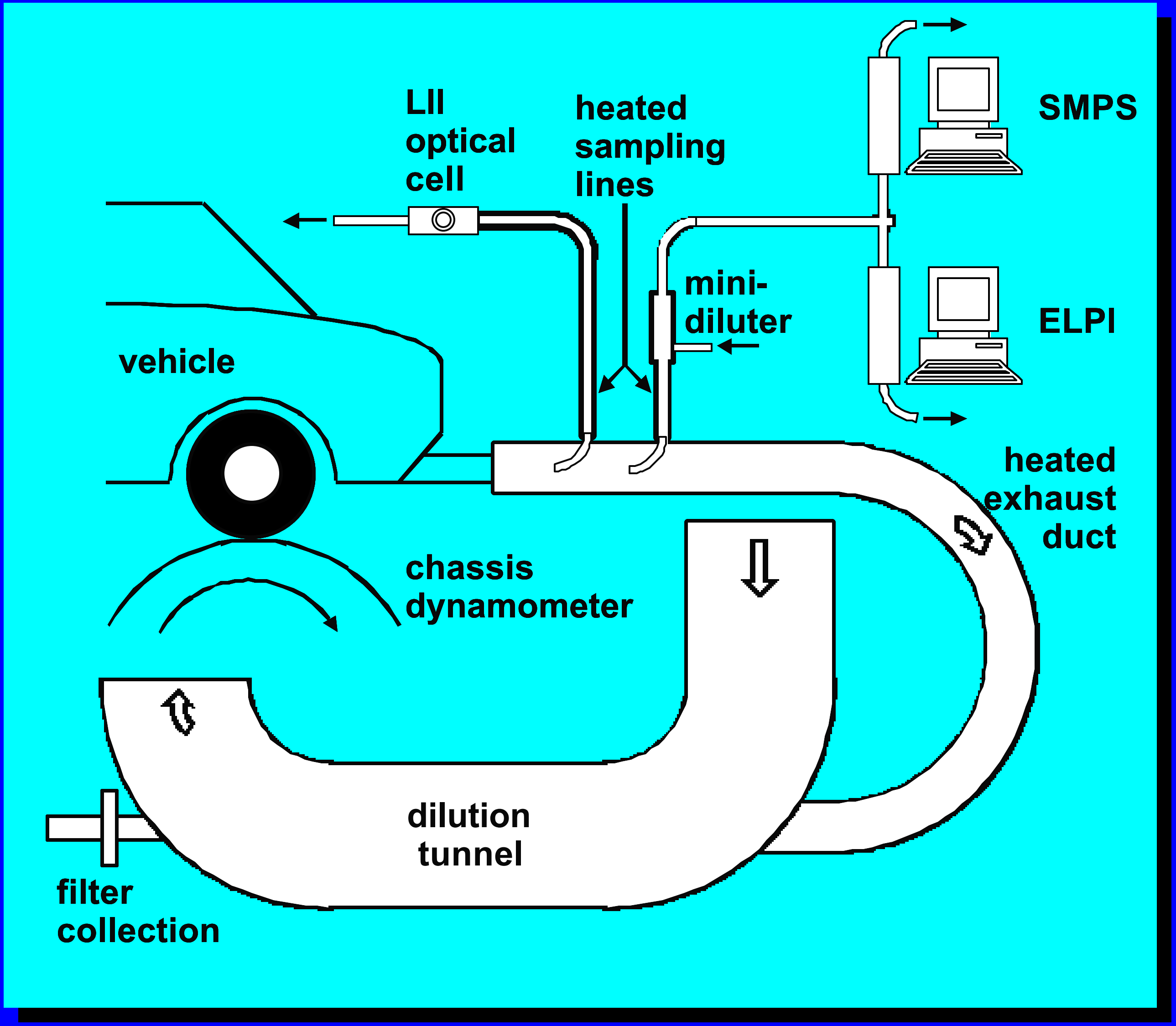
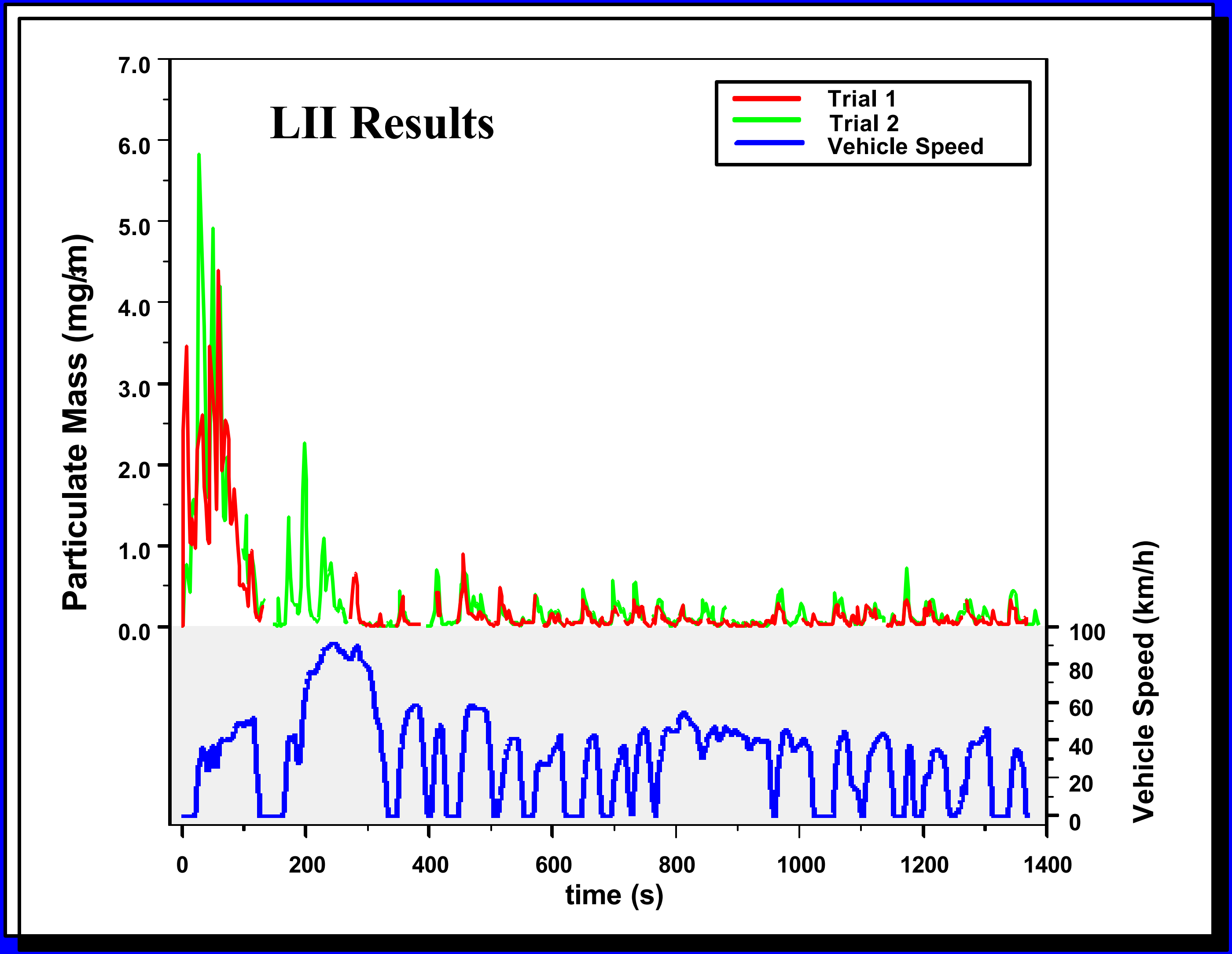
Tailpipe Particulates Measurements



EPA LA4 Cold Start Cycle



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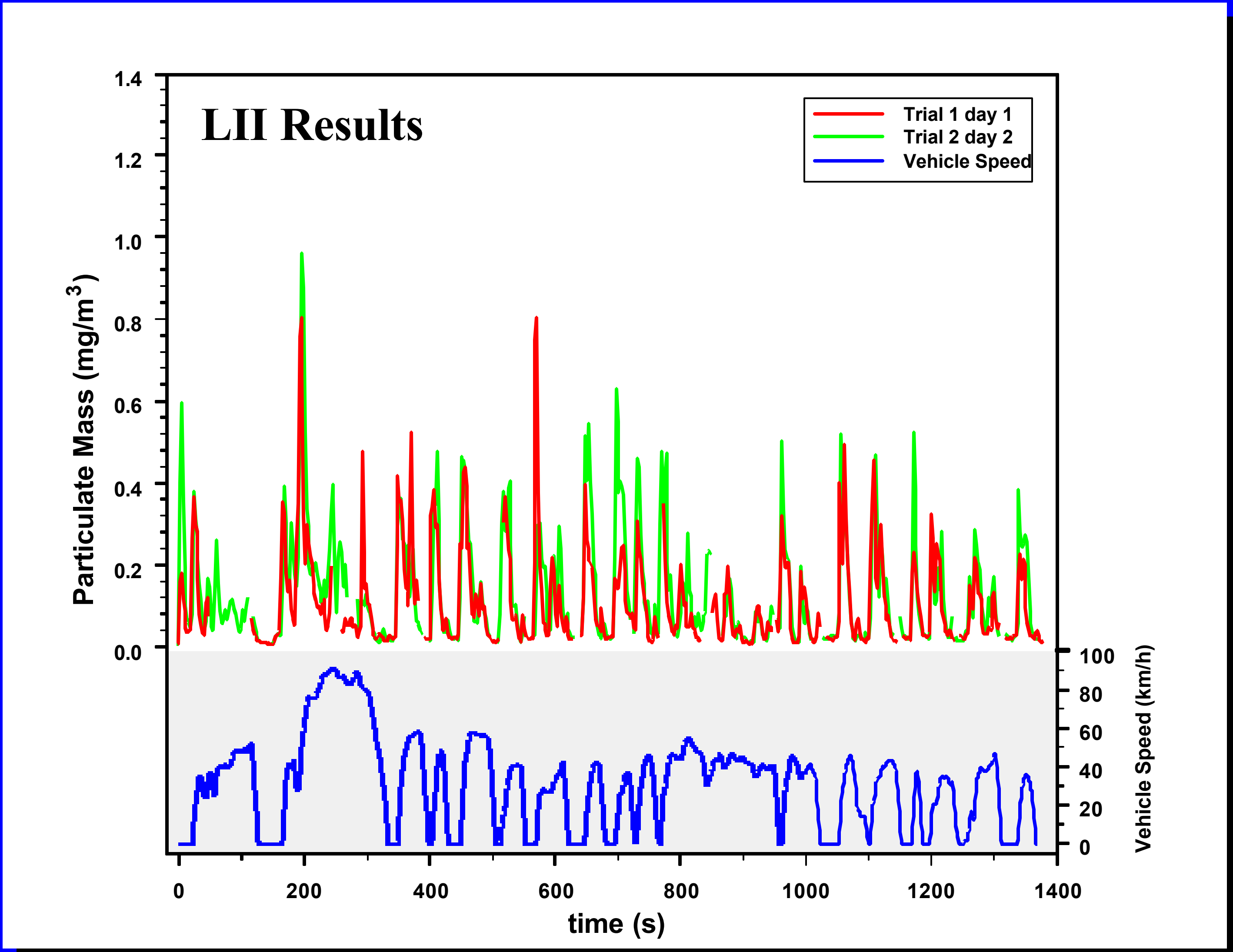
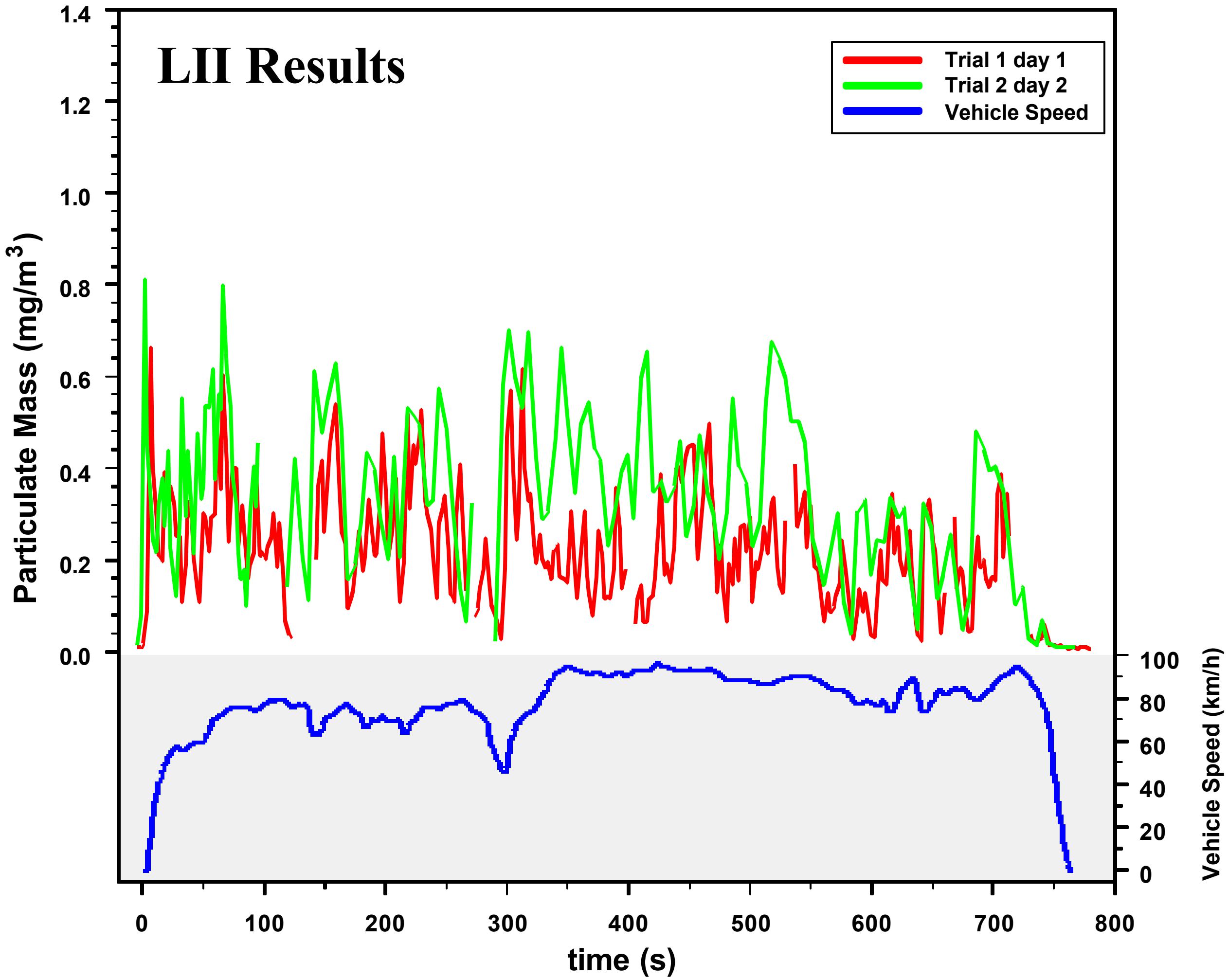
EPA LA4 Hot Start Cycle



HWFET Cycle

Highway Fuel Economy Tests



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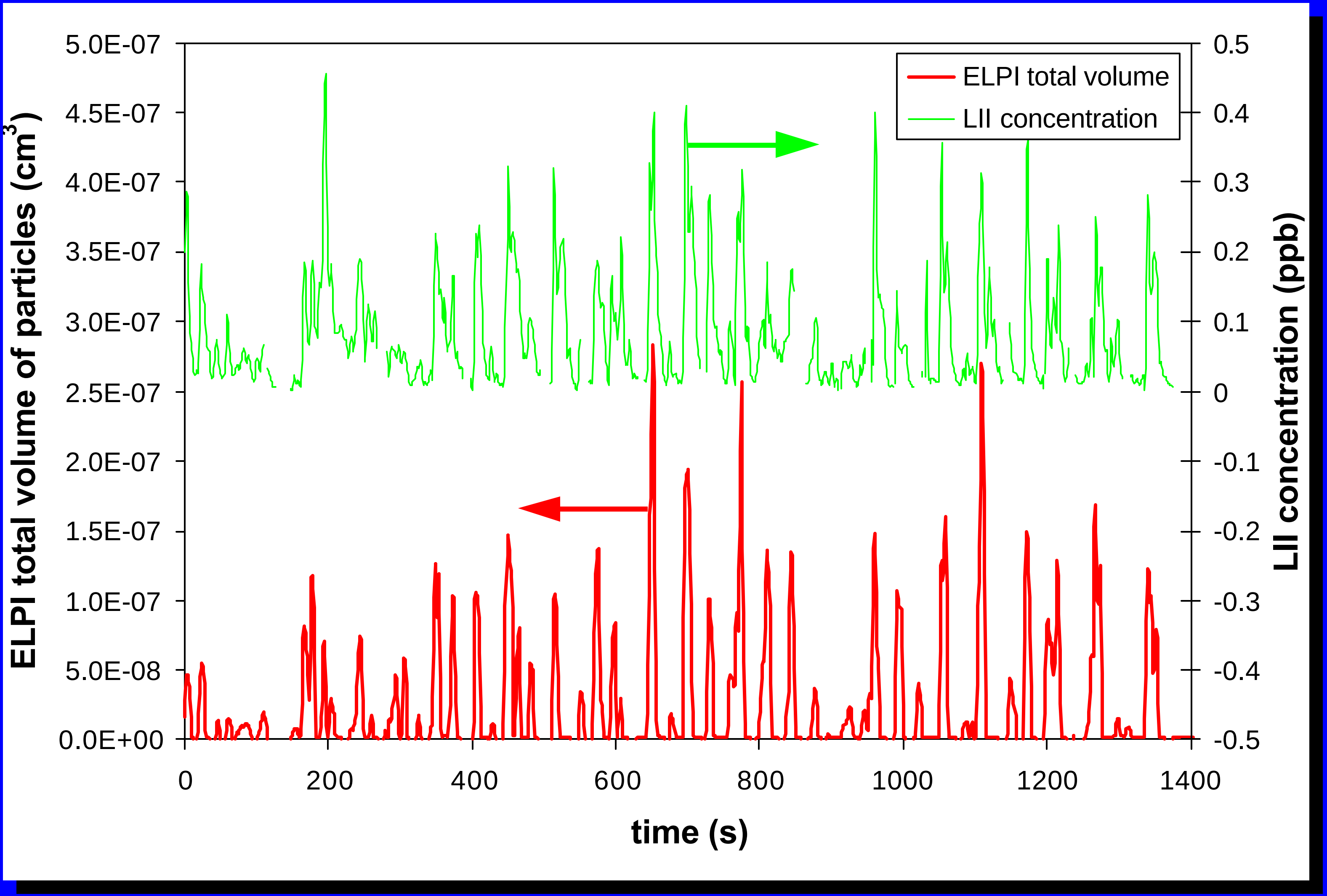
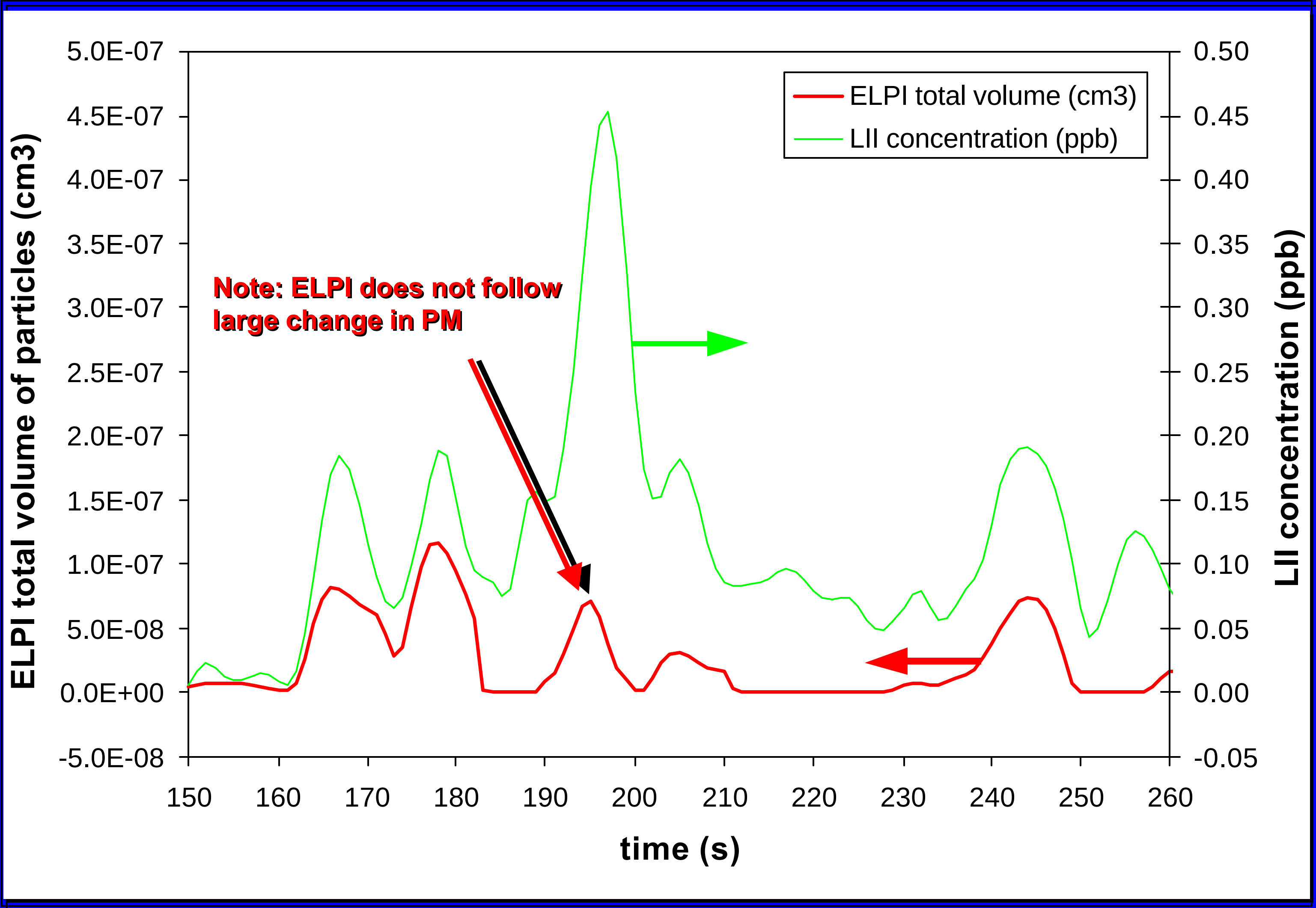
Comparison of particulate levels determined by LII (top) and ELPI (bottom) for hot start LA-4 transient cycle



Detail illustrating relative temporal response and sensitivity of LII and ELPI.



Summary

- LII is a potential method for online monitoring of particulate emissions
- Practical calibration method for measuring soot/particle concentration successfully developed
- LII method has been shown to have a high dynamic range and sensitivity
- Can operate at very low concentrations – post-particulate filter trap
- Measurements can be made without dilution

Summary (continued)

- **Method has very high precision (repeatability)**
- **Comparisons to Gravimetric methods show the potential accuracy of the LII method**
- **LII data comparisons to the SMPS and ELPI demonstrate the superior time response and capability in measuring transient particle emissions**
- **LII combined with other methods may best fulfill future monitoring requirements**