High-Energy, Pulsed-Laser Diagnostics for Real-Time Measurements of Reciprocating Engine PM Emissions

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Outline

- Motivation
- Overview of High-Energy Laser Diagnostic (HELD) techniques
- HELD specifics and example applications
- Technology transfer (national lab to customer)
- Commercialization (industry to customer)
- Summary of HELD status

Motivation for HELD R&D

- Sensitive PM measurement techniques are needed to study cleaner vehicles

- Real-time PM measurement techniques are needed to investigate transients

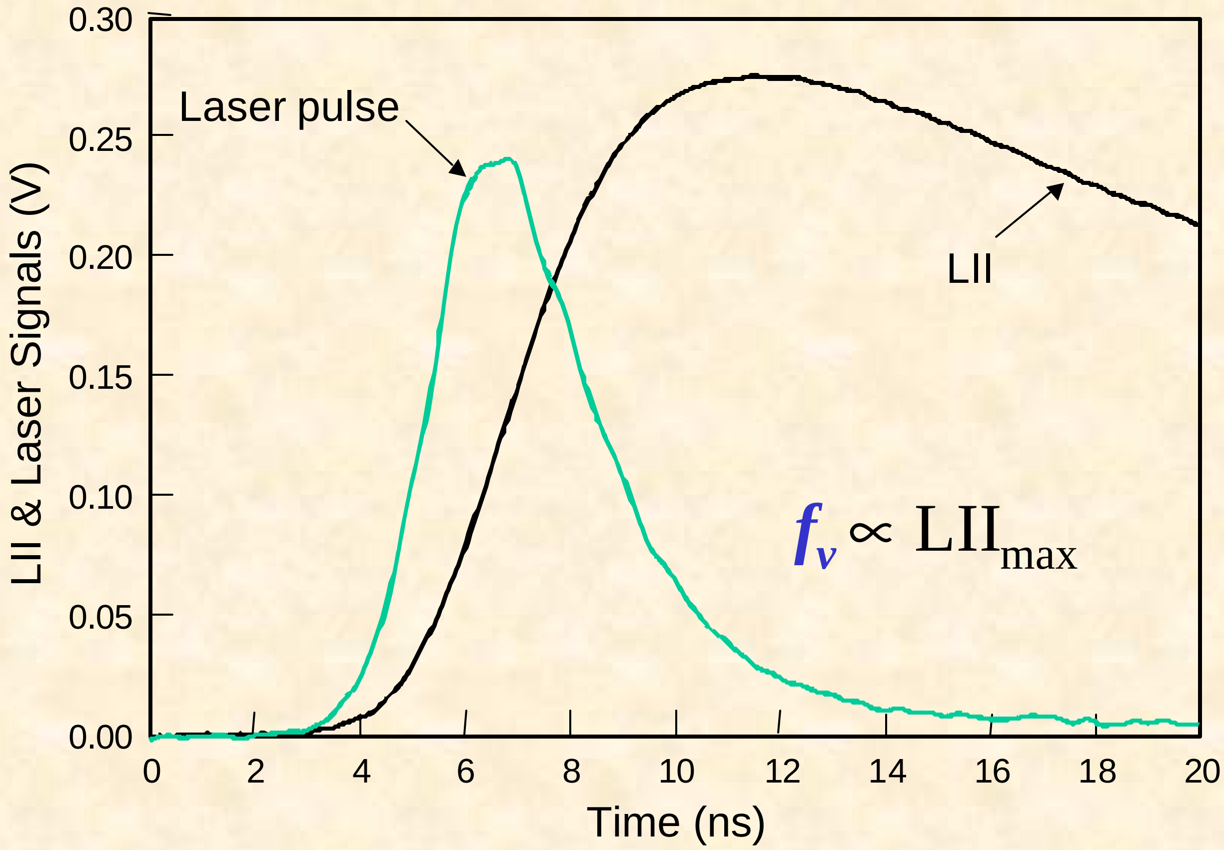
★ *In situ* PM measurement techniques are needed to characterize engine-out/aftertreatment-in conditions for design optimization and life-cycle simulations

HELD techniques for PM measurements

- Laser-induced incandescence (LII) for inorganic carbon (soot) volume fraction and primary particle size
- Elastic light scattering (ELS) for total volume fraction
- LII + ELS for aggregate size, number, and structure
- Laser-induced desorption (LID) + ELS (LIDELS) for volatile volume fraction
- Laser-induced breakdown spectroscopy (LIBS) for metallic ash (species and concentration)
- Laser-induced fluorescence (LIF) for composition

LII for volume fraction f_v

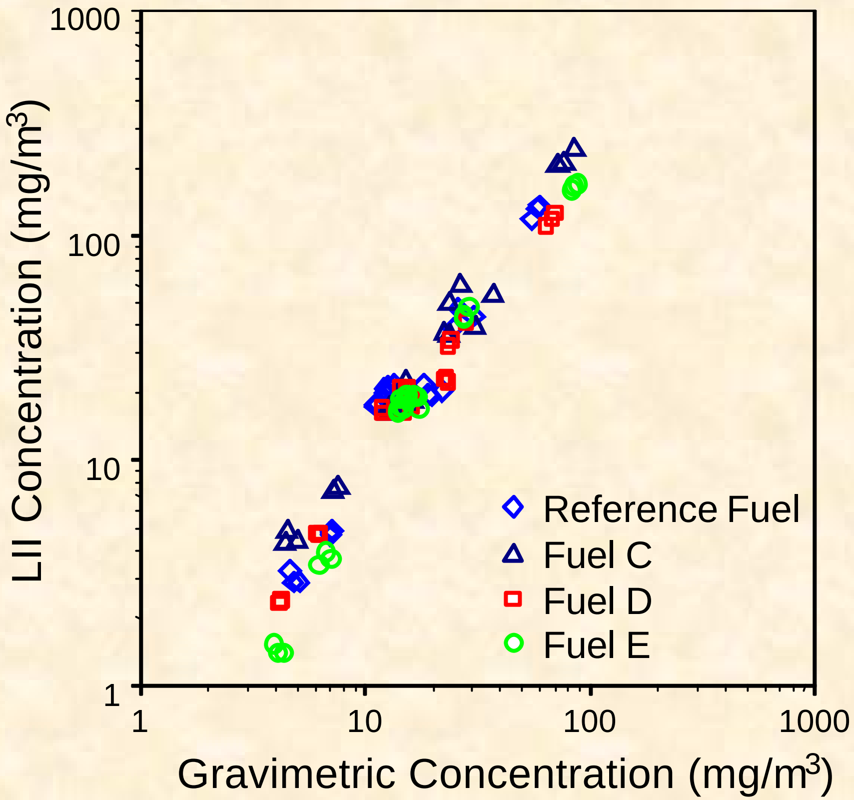
- High-energy laser pulse heats PM to sublimation temperature of carbon
- Black-body radiation is proportional to soot volume fraction



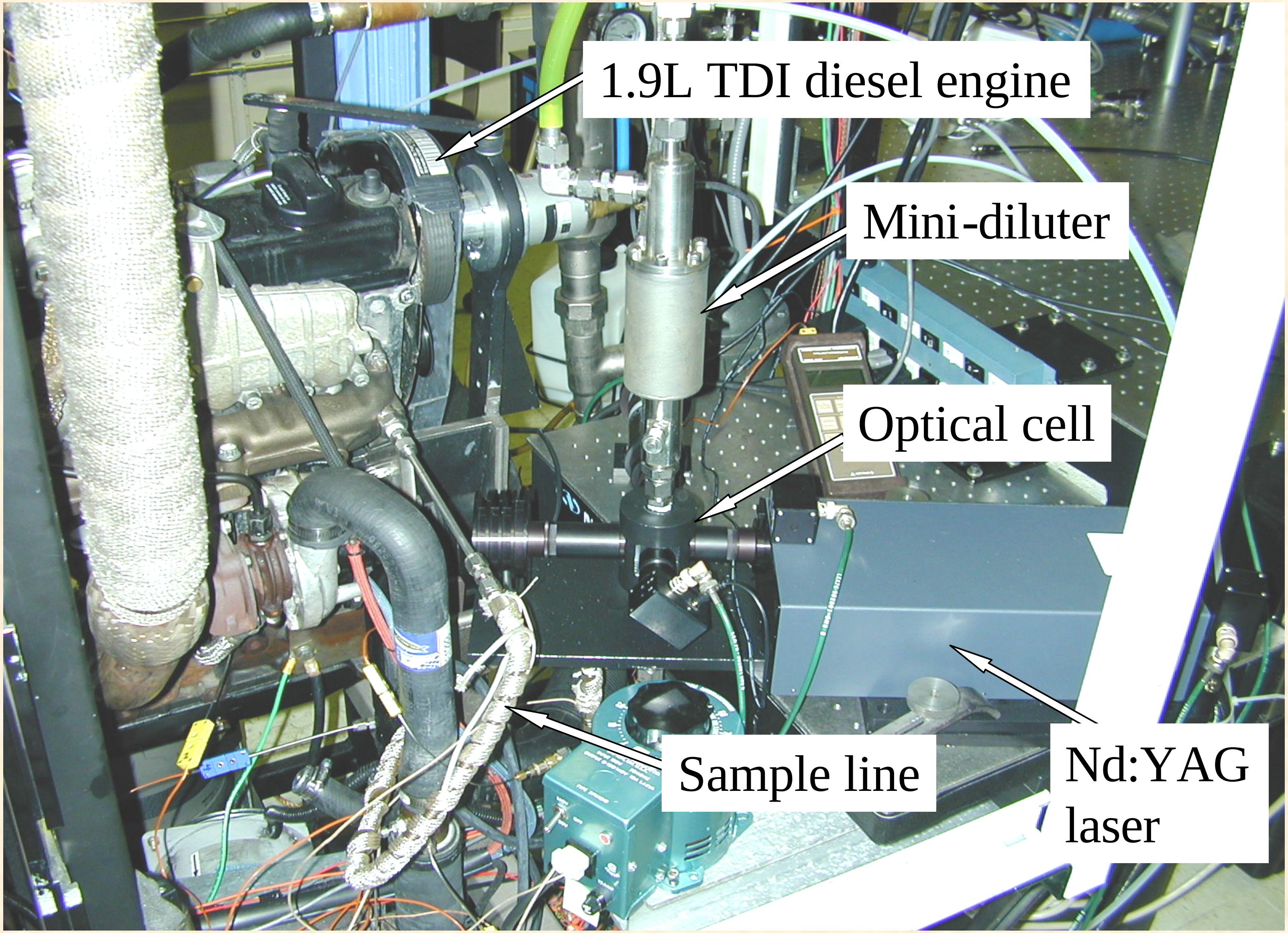
$$f_v \propto \mathrm{LII}_{max}$$

Correlation of LII and gravimetric methods

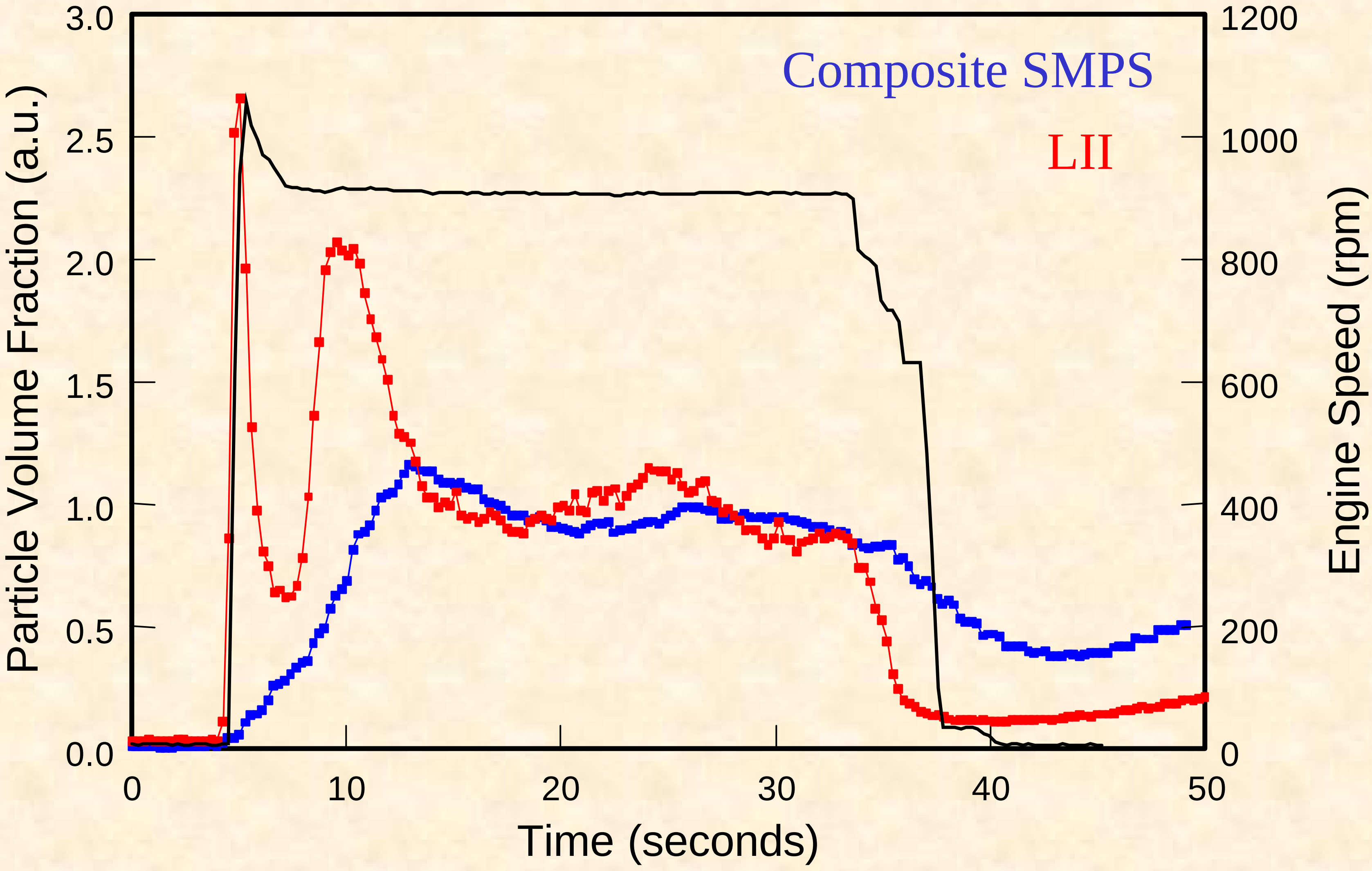
Measurements for the AVL 8-mode steady-state simulation of US EPA heavy-duty transient test procedure



Continuous exhaust sampling

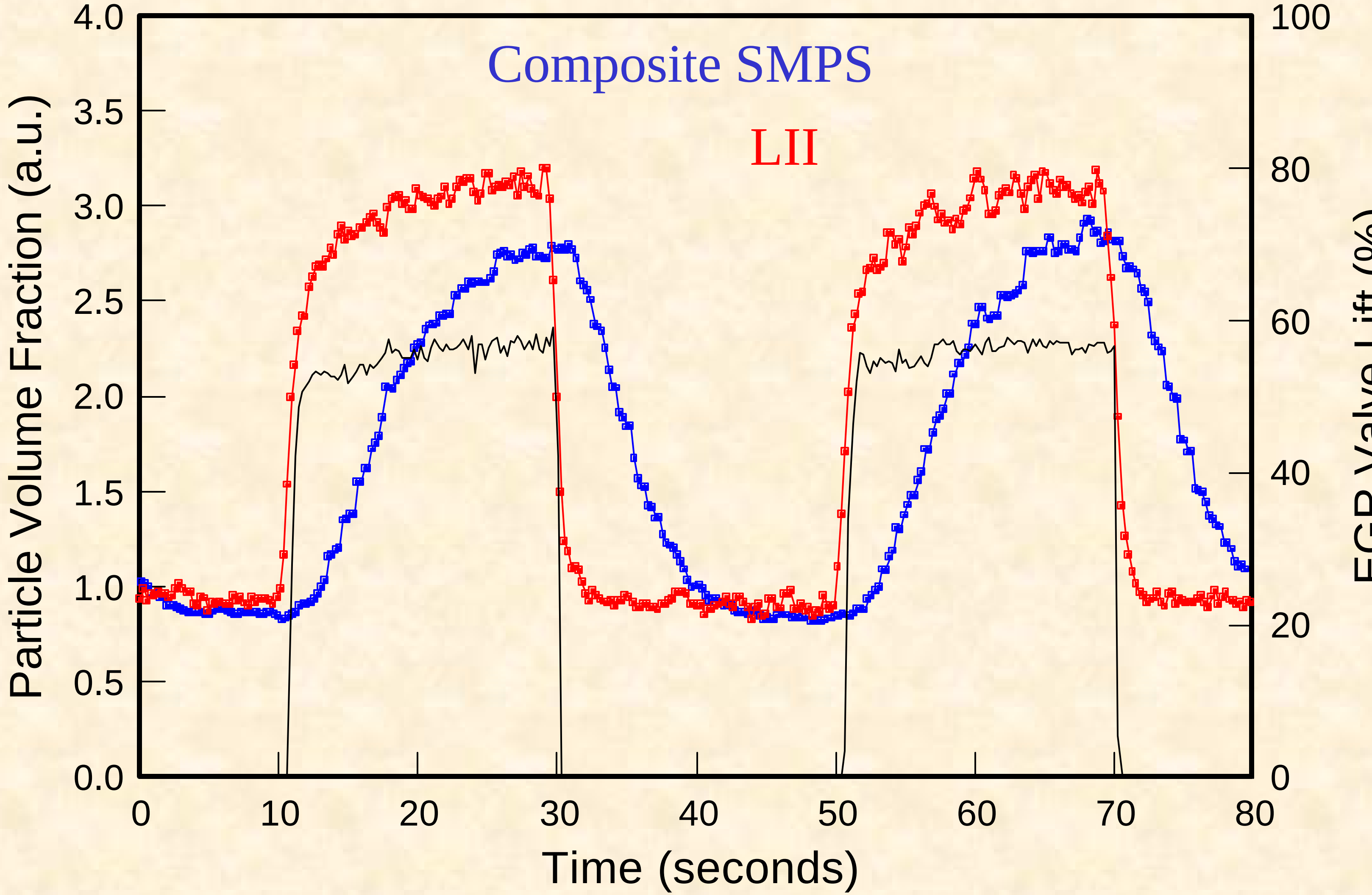


Speed-transient measurements of f_v



SAE 2001-01-3574

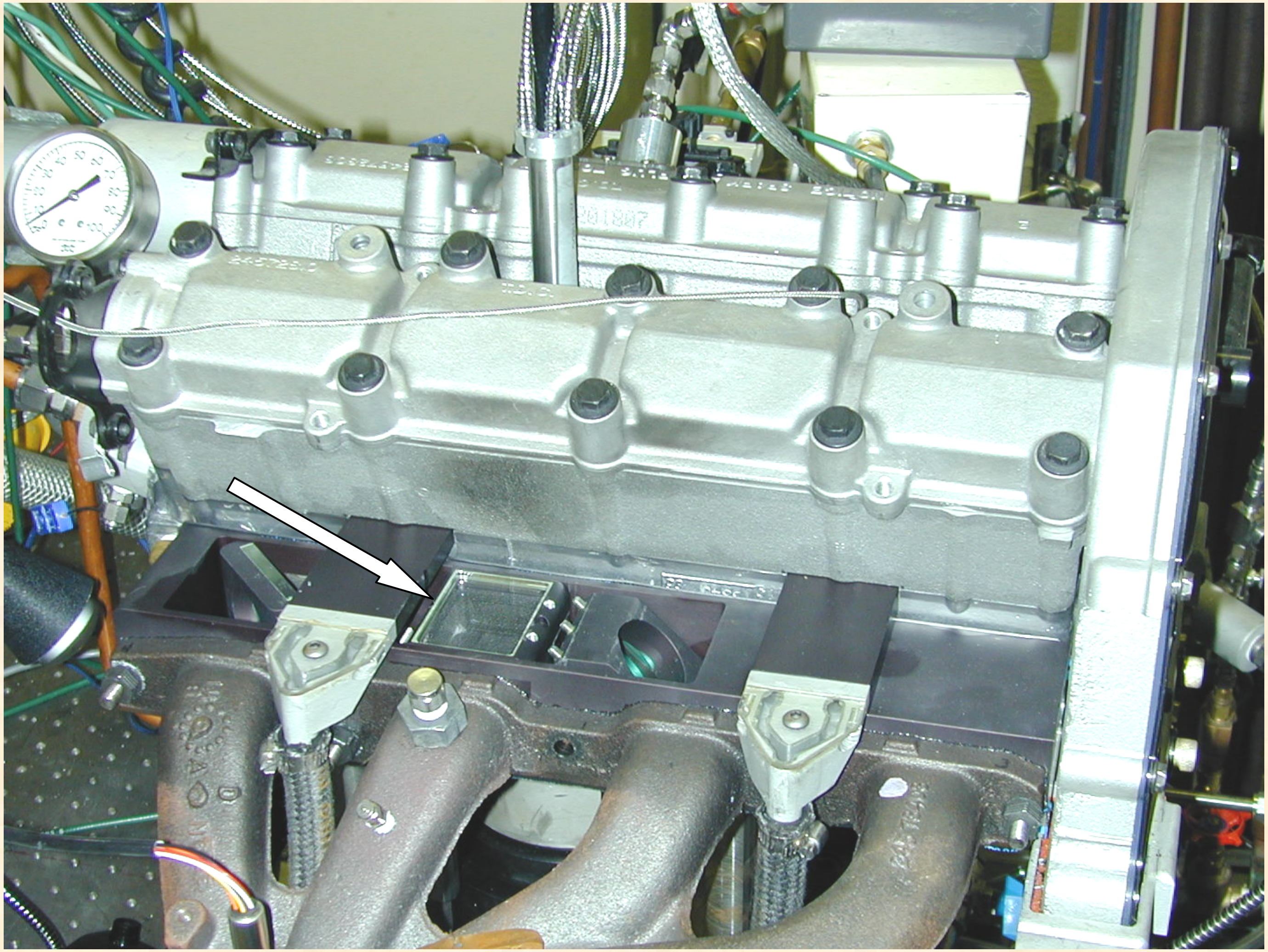
EGR-transient measurements of f_v



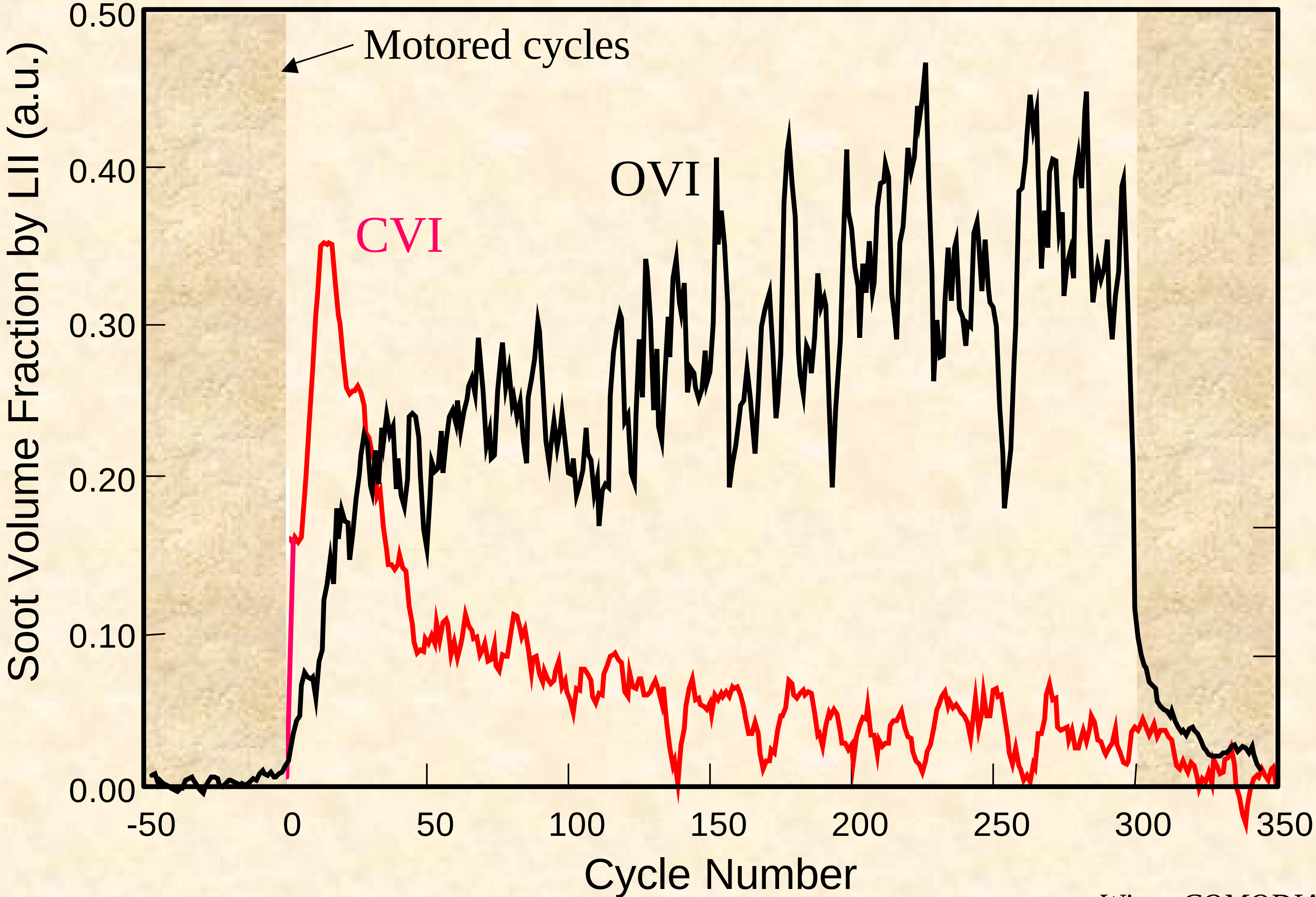
SAE 2001-01-3574

Exhaust-port optical cell for *in situ* measurements

1994 GM Quad-4 PFI engine

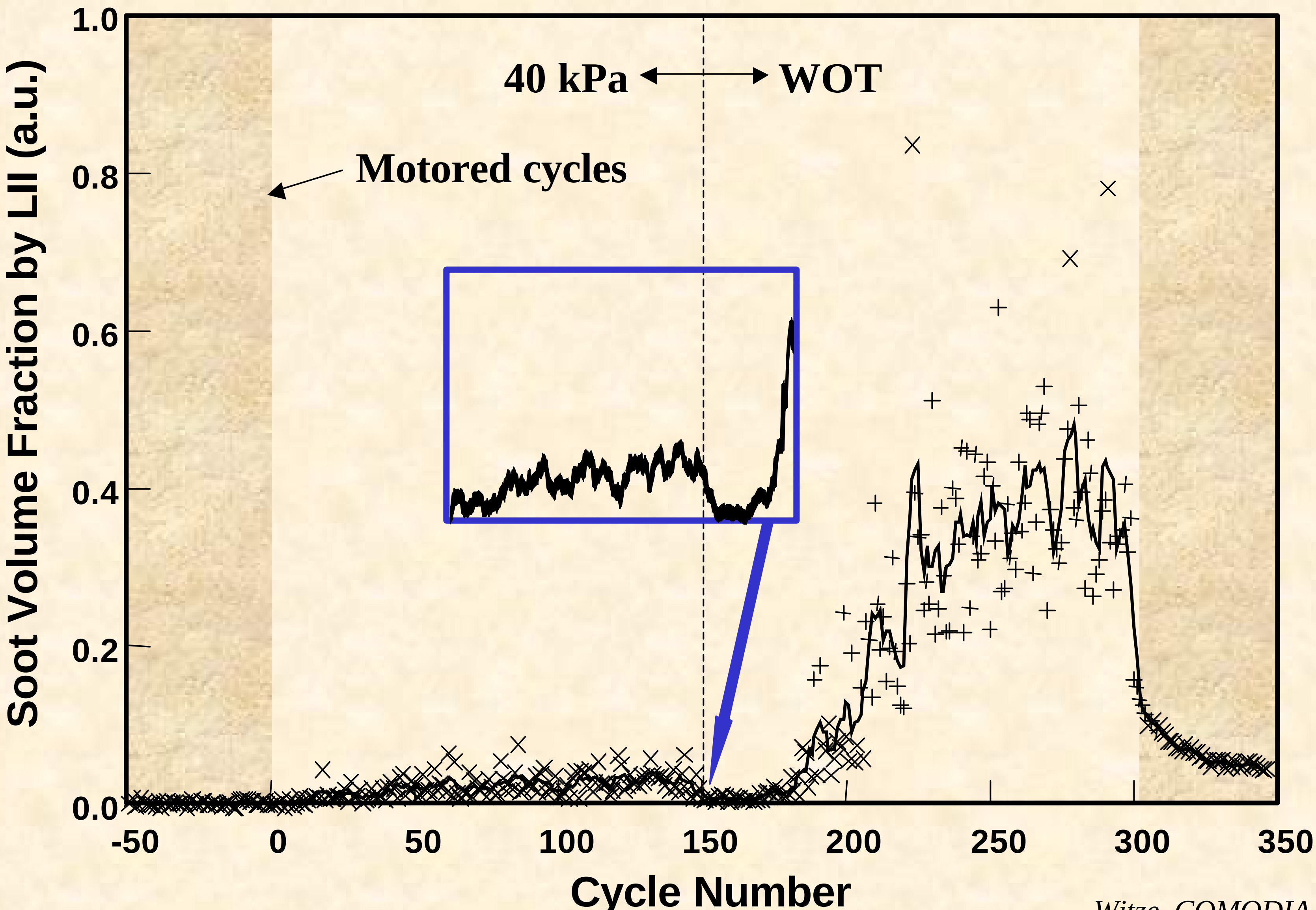


Simulated cold-start transient, ϕ=1.24



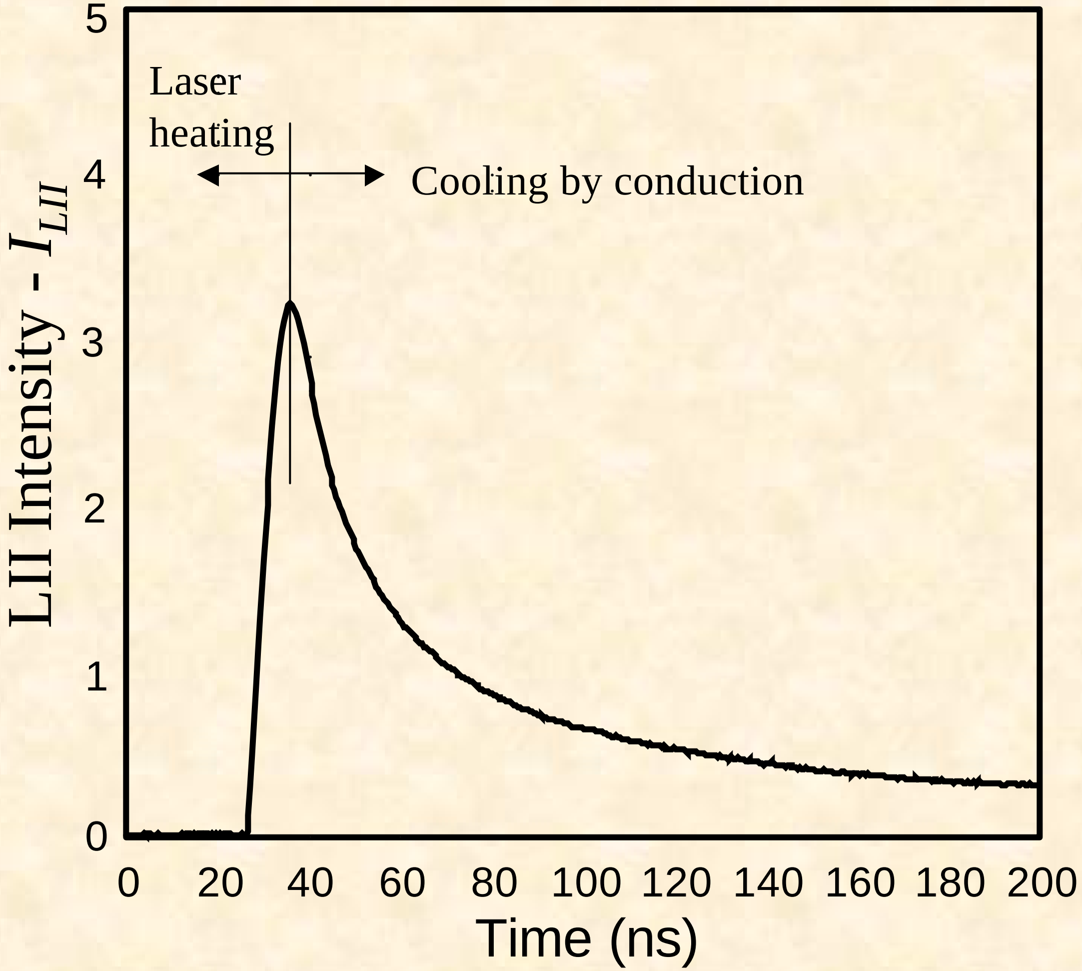
Witze, COMODIA 2001

Snap-throttle transient, ϕ=1.0, OVI



Witze, COMODIA 2001

LII for primary particle diameter ***d*** and number ***n***



$$I_{LII} \propto T^5$$

$$T(t) \propto e^{-\frac{k}{d}t}$$

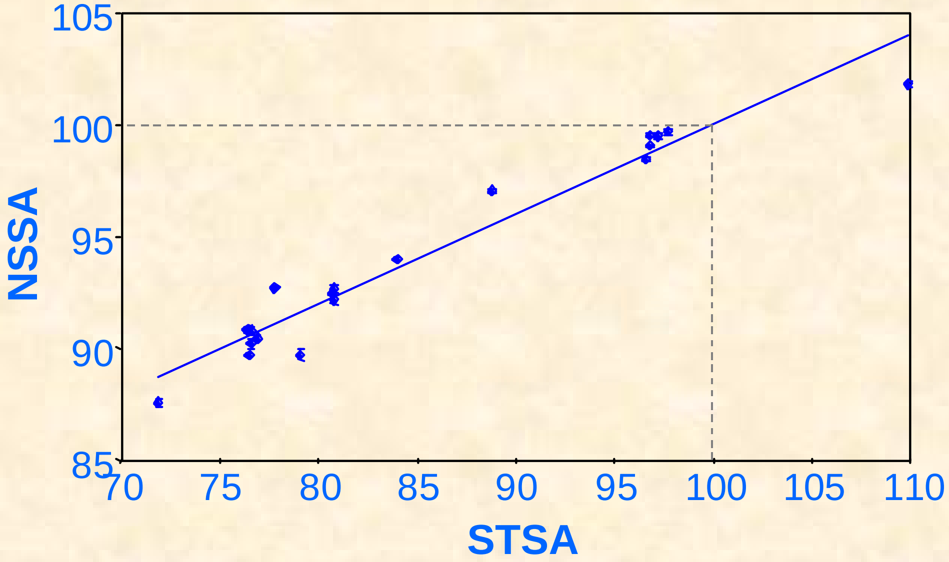
↓

d

$$\boldsymbol{n} = f_v / d^3$$

LII measurements of ***d*** and ***n*** for carbon black

LII test site at carbon black plant



Normalized specific surface area (NSSA) determined by LII is closely correlated with conventional statistical thickness surface area (STSA).

LII + ELS for aggregate size *D* and number *N*

if $I_{\mathrm{ELS}} \propto V^2 = ND^6$

$I_{\mathrm{LII}} \propto V = nd^3 = ND^3$

where n = # primary particles

d = primary particle diameter

N = # aggregates

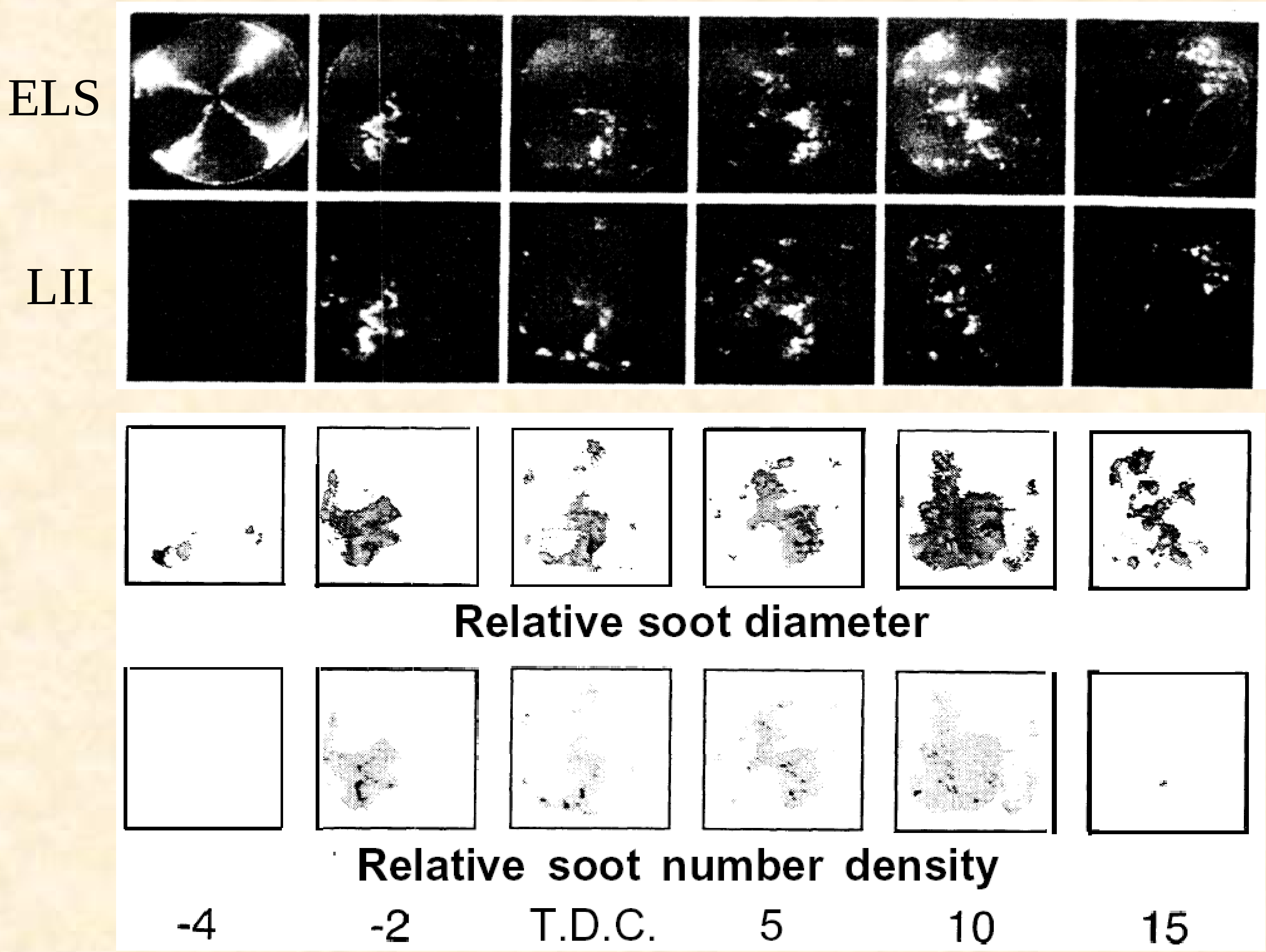
D = equivalent-sphere aggregate diameter

then

$$\frac{I_{\mathrm{ELS}}}{I_{\mathrm{LII}}} \propto \frac{ND^6}{ND^3} = \boldsymbol{D^3}$$

$$f_v / D^3 = \boldsymbol{N}$$

LII + ELS images of ***D*** and ***N*** for diesel combustion



Fujimoto et al., SAE 982630

RDG/PFA for aggregate structure

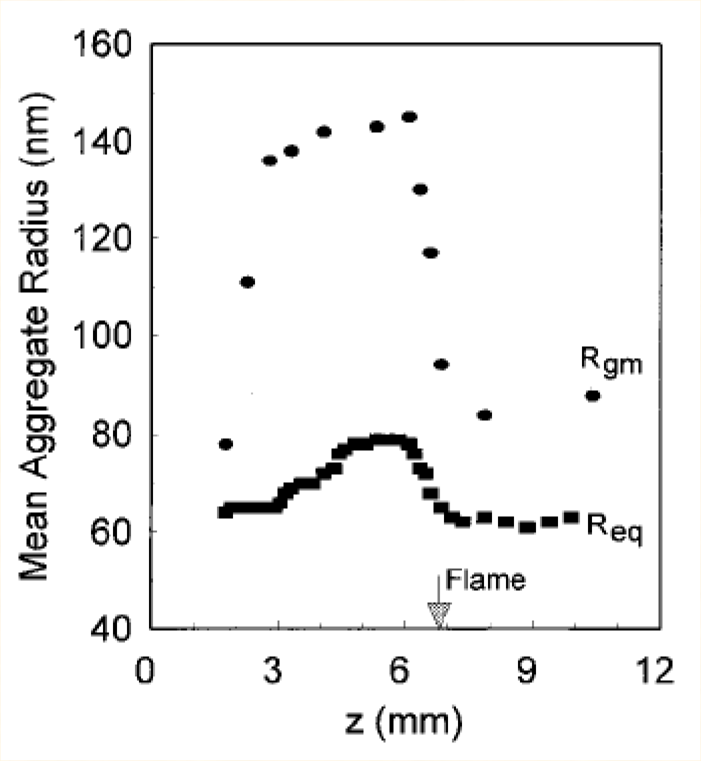
Rayleigh-Debye-Gans polydisperse fractal aggregate theory

(ELS with 3-angle detection)

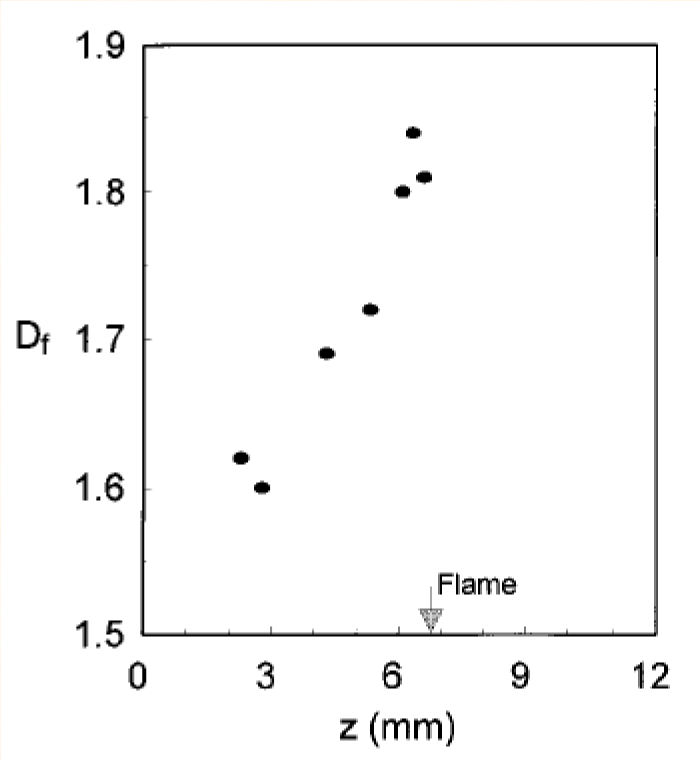
$\overline{N}_{p/a}$	geometric mean of number of primary particles per aggregate (assumed log-normal distribution)
$s_{p/a}$	geometric standard deviation of number of primary particles per aggregate
D_f	fractal dimension (irregularity of shape)
S	aggregate surface area per unit volume
R_a	radius of gyration of an aggregate

RDG/PFA for R_{gm}, R_{eq} and D_f

Al_2O_3 aggregates produced in a laminar counterflow nonpremixed methane flame



Mean aggregate radius of gyration R_{gm} and volume-equivalent radius R_{eq}



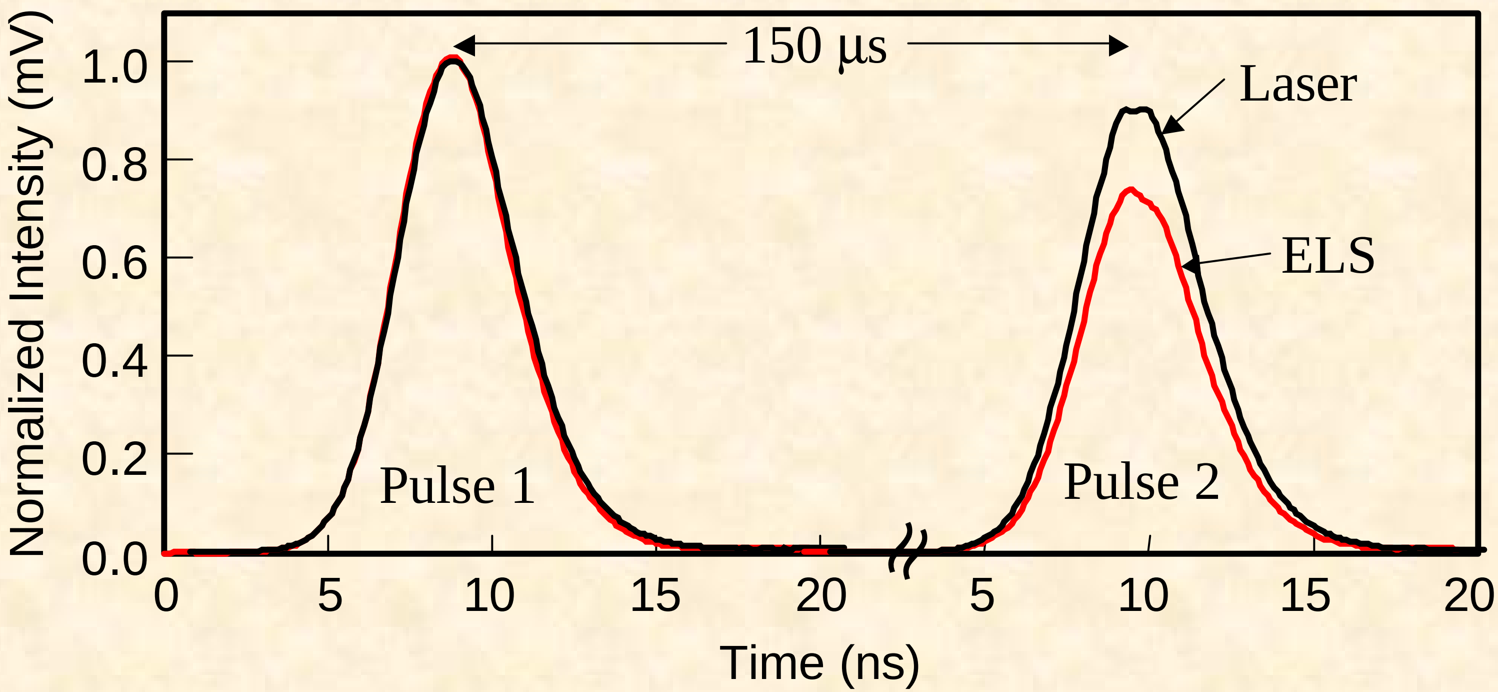
Aggregate fractal dimension

Xing et al., Applied Optics 38:2686-2697, 1999

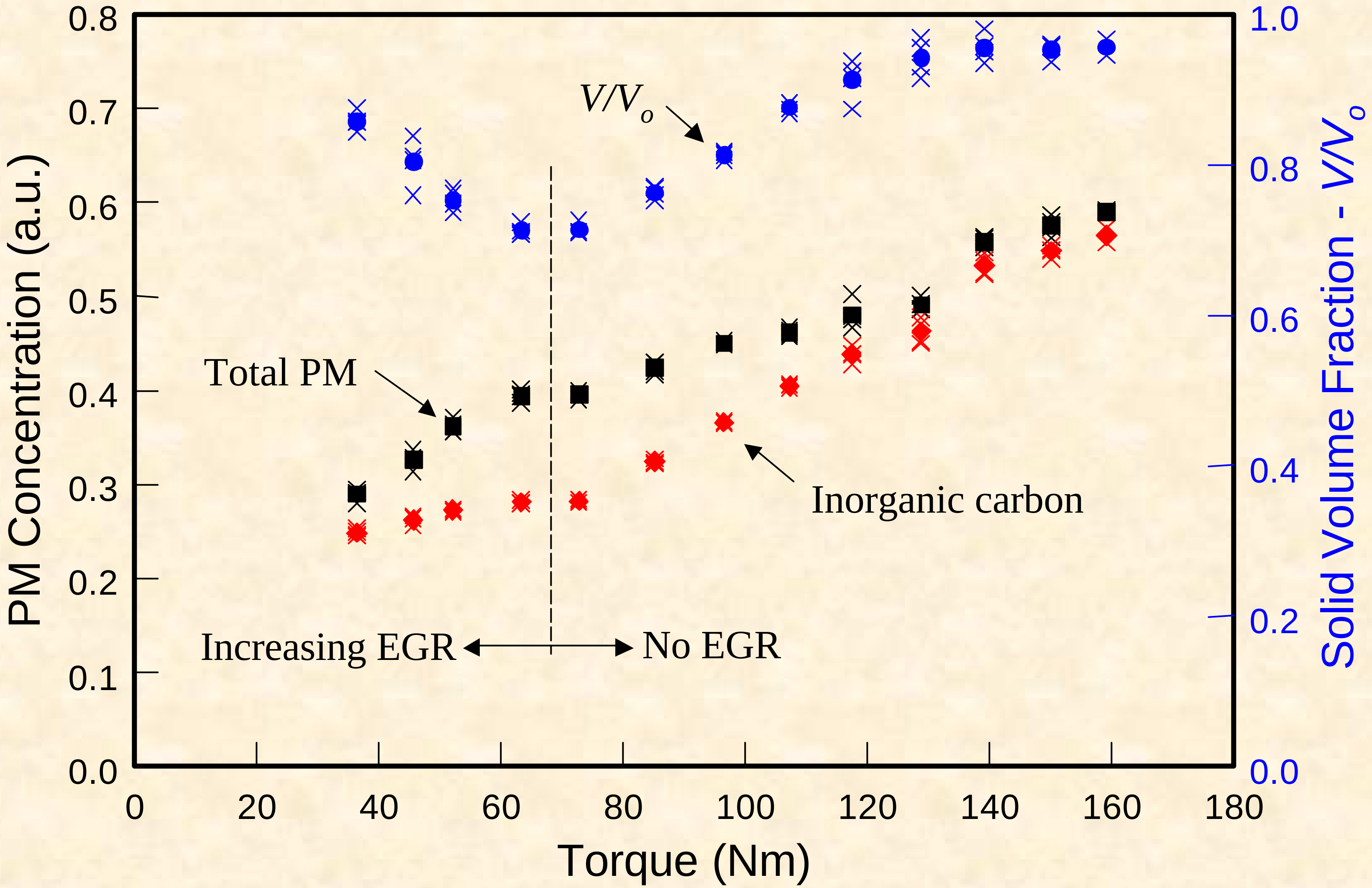
Laser-induced desorption (LID) + ELS (LIDELS)

Double-pulse laser with 150 μs interval

The ratio of ELS measurements before and after LID of volatile matter gives the solid fraction (**SOL**) in real-time



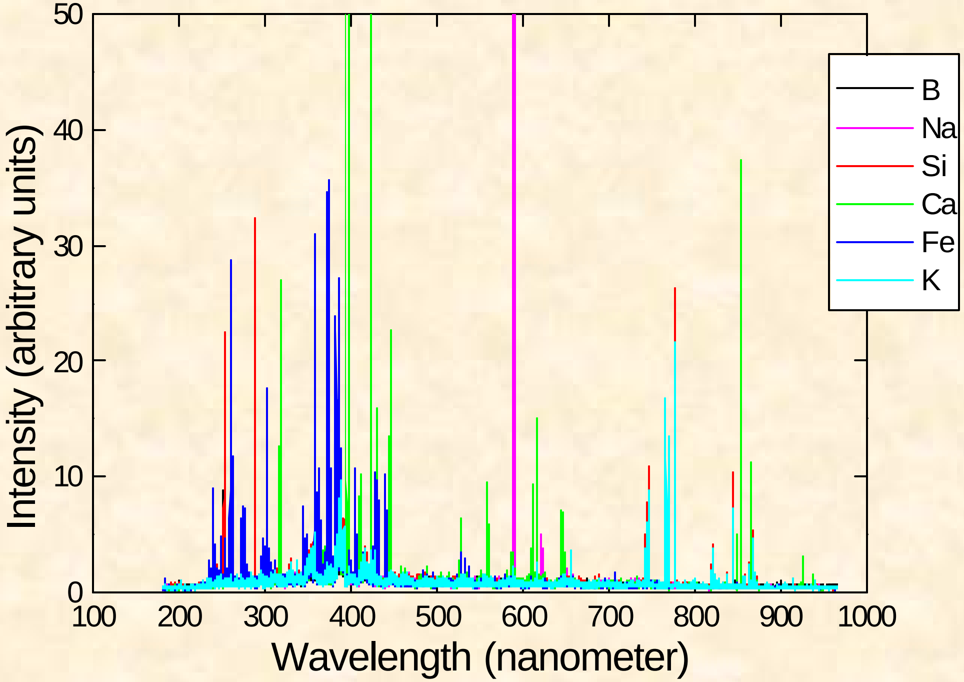
LIDELS load sweep for **SOL**



SAE 2002-01-1685

Laser-induced breakdown spectroscopy (LIBS)

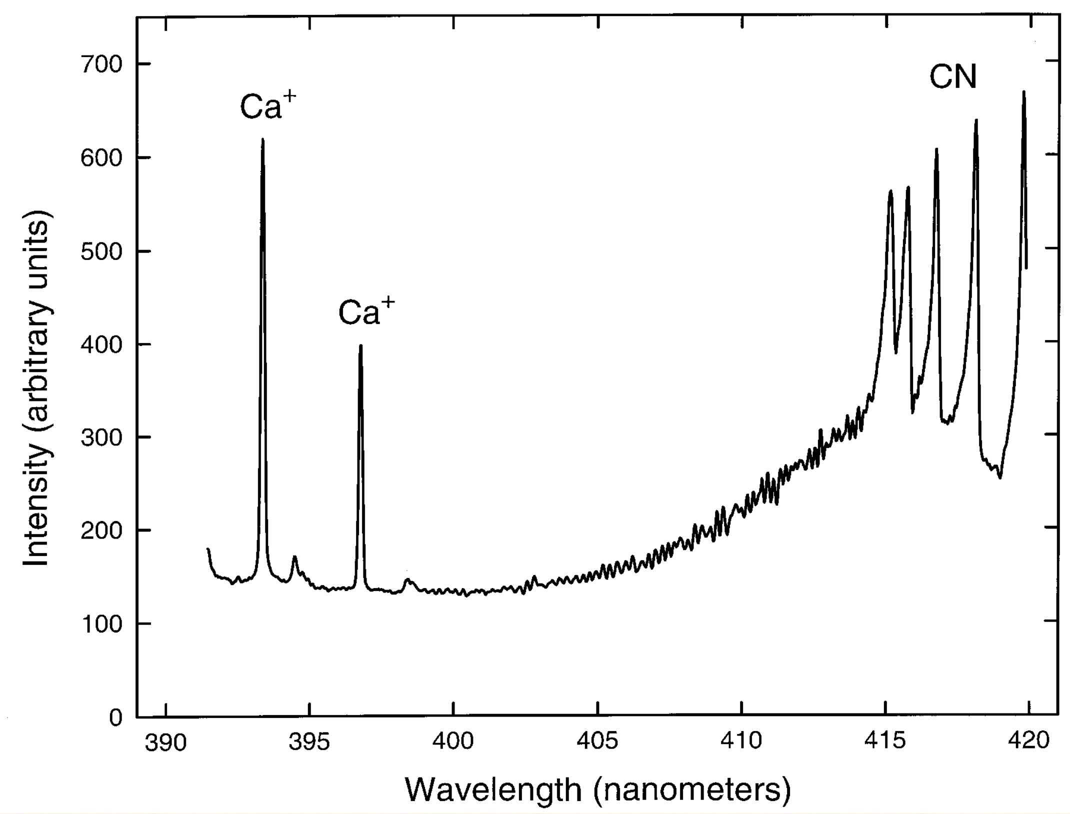
- Laser-induced spark causes atomic emissions from metallic elements
- Line position provides species identification
- Line intensity provides species concentration ***C***



LIBS calibration spectra

LIBS measurements for *C*

LIBS measurements of calcium in the exhaust of a stationary, natural-gas-fueled SI engine provide a measure of oil consumption



(*Walsh et al., 94th Annual Conference, Air & Waste Management Association, Orlando, FL, June 24-28, 2001, Paper No. 867*)

Technology Transfer

CIDI team at GMR R&D is interested in both the LII and LIDELS techniques.

We are building a portable, stand-alone system to take to their facilities for demonstration and evaluation.

System requirements:

- Tap into exhaust line
- Tap into vent line
- 110 v power

Target date: Fall, 2002

2’ x 4’ cart

General Motors R&D Center
CIDI Vehicle Emissions Laboratory

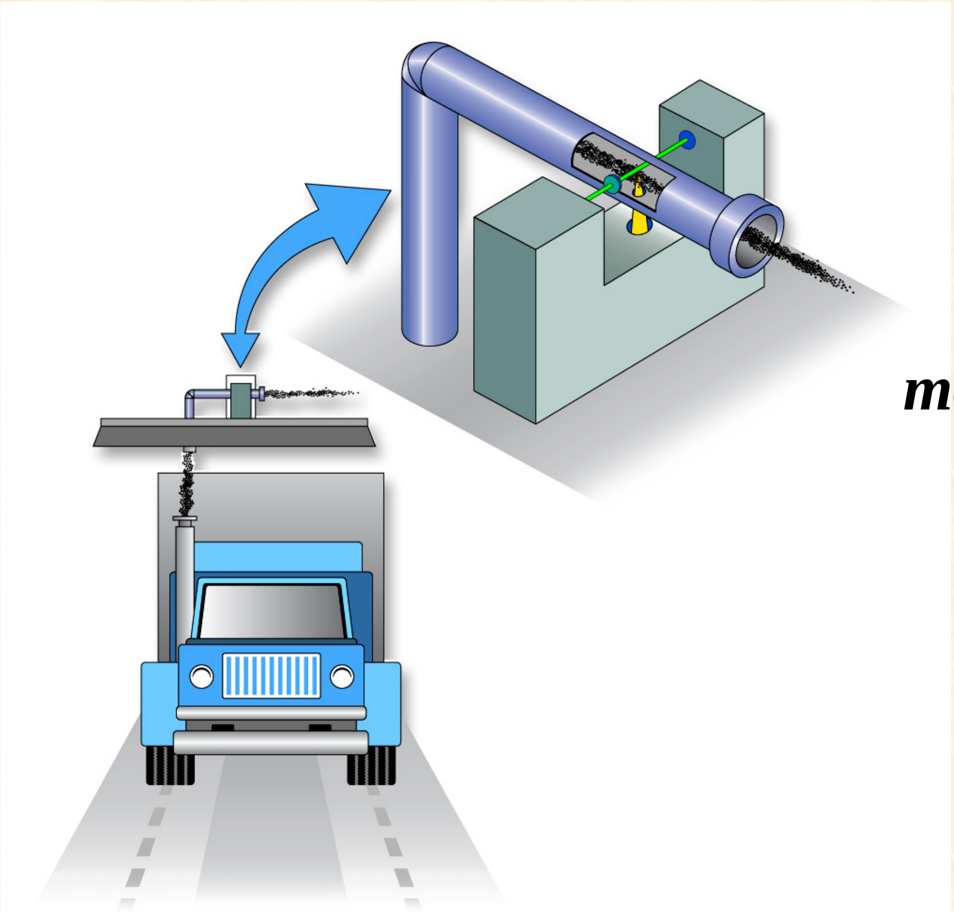
Particulate Matter Collaboratory web page

NRC · CNRC Combustion Research

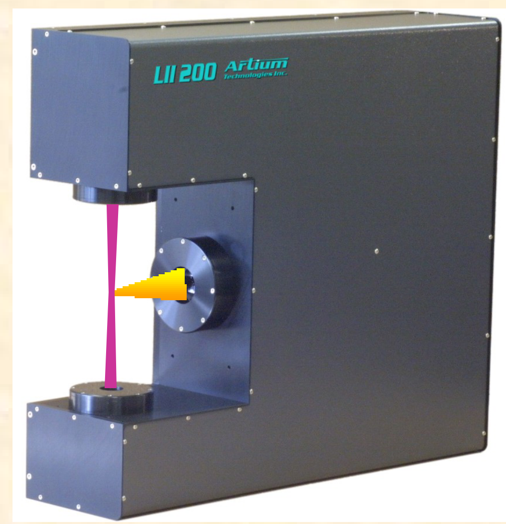
Artium Technologies Inc.

Artium Technologies Inc.

Commercialization



Collaborating to develop, evaluate, and commercialize LII systems for online monitoring of exhaust PM



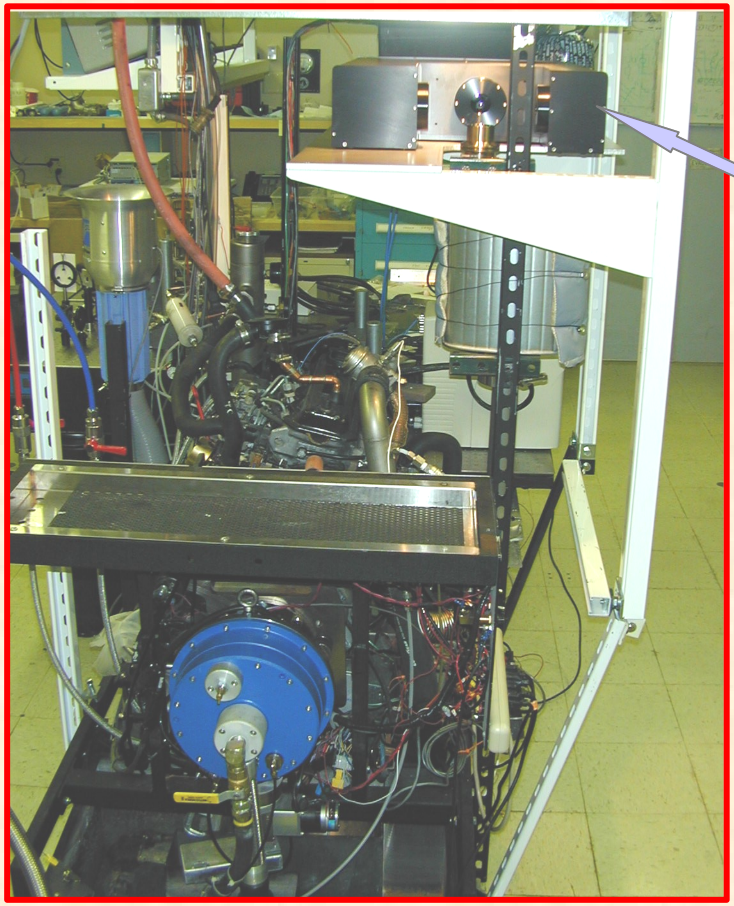
NRC · CNRC

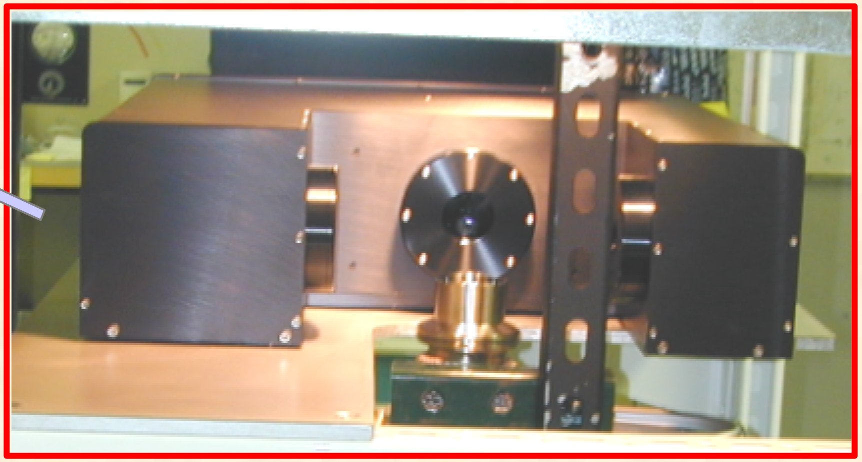
Combustion Research

Artium Technologies Inc.

Implementation – open exhaust

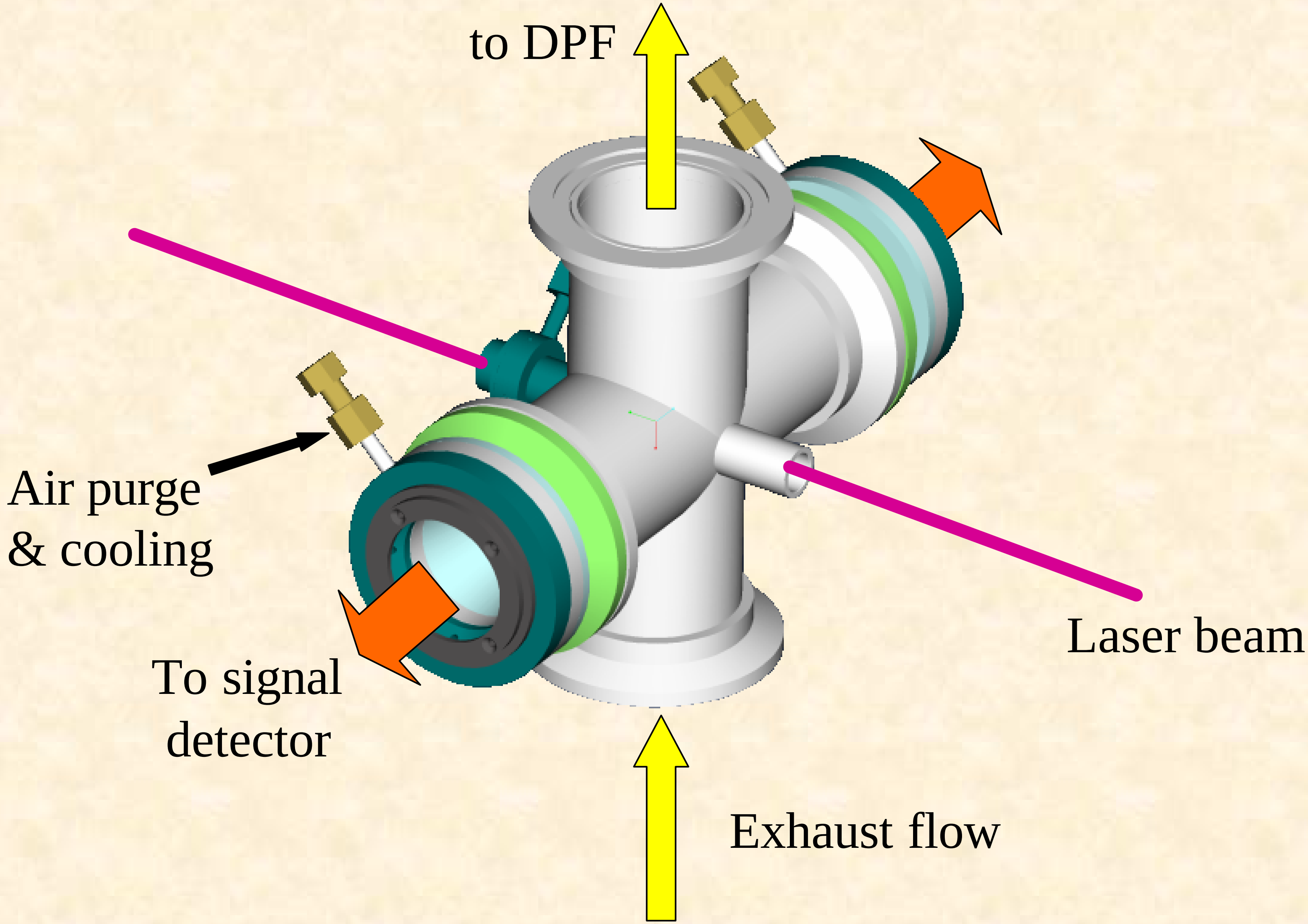
The Sandia Combustion Research Facility is providing facilities and support for testing and evaluating the commercial product, in addition to advice on design and development. The engine shown is a 1996 Volkswagen 1.9L TDI diesel.





The LII instrument is located on a shelf under a ventilation hood. For the application shown, the measurements are obtained in the open exhaust after the muffler. We also have the capability to use an inline optical cell for in situ measurements, enabling us, for example, to measure soot concentrations entering and exiting a DPF (diesel particulate filter).

Implementation – in line



Summary - Status of HELD techniques

- Commercial LII instruments already exist for volume fraction and primary particle size
- LII + ELS for aggregate size and number has been demonstrated in laboratory flames and in-cylinder for diesel engines
- RDG/PFA has been demonstrated only in laboratory flames
- LIDELS has been demonstrated on diesel exhaust, but need validation of VOF measurement and calibration for TPM
- LIBS has been demonstrated for a natural-gas-fueled stationary engine