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High Spatial Resolution Laser Cavity Extinction Measurements of Soot Volume Fraction In Low Soot Producing Flames

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- Cambridge Particle Meeting 2014

Motivation

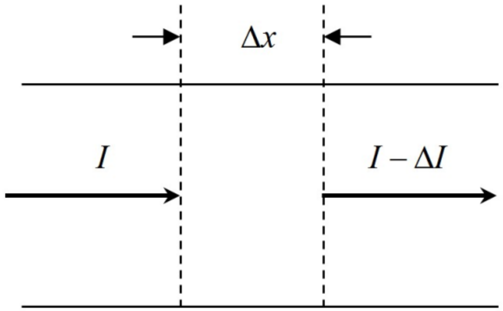
- Measurements of non-intrusive soot volume fraction in flames are important in understanding pollutant formation
- Typical methods are laser induced incandescence (LII) and extinction

	LII	Extinction
Absolutely quantitative	×	√
High spatial resolution	√	×
High sensitivity	√	×
Short response time	×	√
Low cost	×	√

- The *sensitivity* and *resolution* of extinction measurements can be improved by using a laser absorption cavity.

Theory of extinction measurement

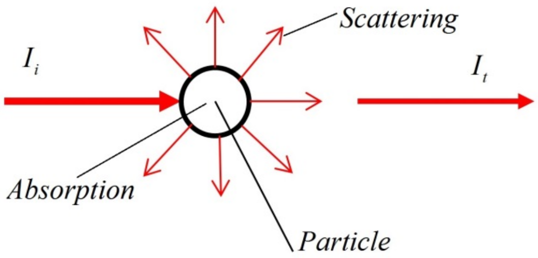
- Lambert-Beer Law [1,2]



$$\frac{\Delta I}{I} = -K_{ext}\Delta x \qquad (1)$$

$$-\ln\frac{I_{transmitted}}{I_{incident}} = \int_{-\infty}^{+\infty} K_{ext}\,\mathrm{d}x = P \qquad (2)$$

- Rayleigh approximation[3]



Size parameter *d:*

$$d = \frac{2\pi r}{\lambda}$$

$\lambda = 638$ nm $\qquad r \leq 15$ nm[4]

For *d*<<1 : Rayleigh limit, scattering is negligible

$$K_{ext} = \frac{6\pi E(m)}{\lambda} f_v$$

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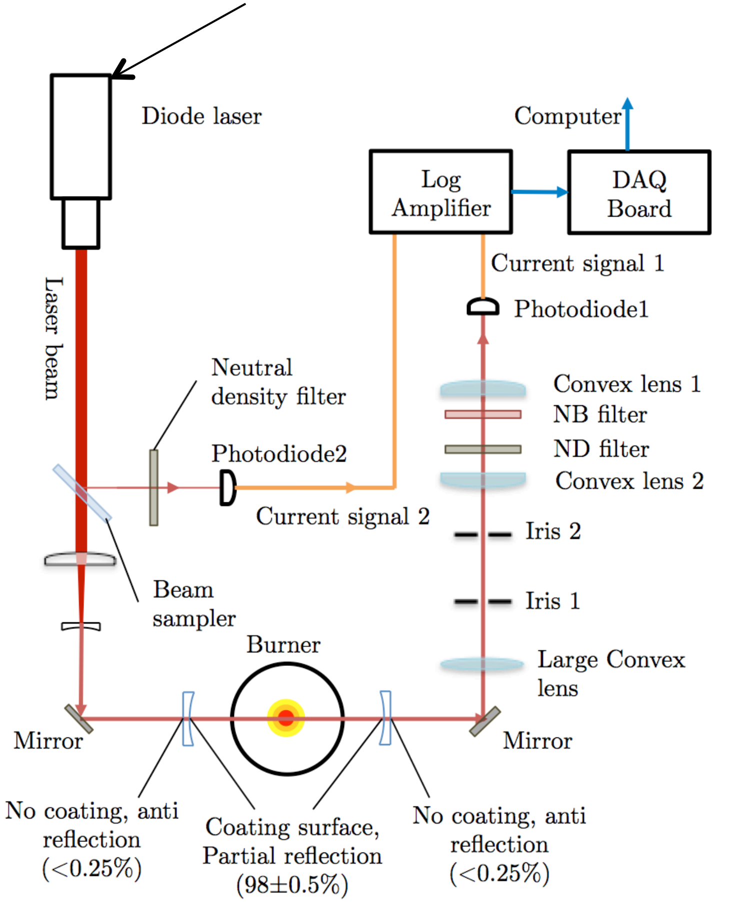
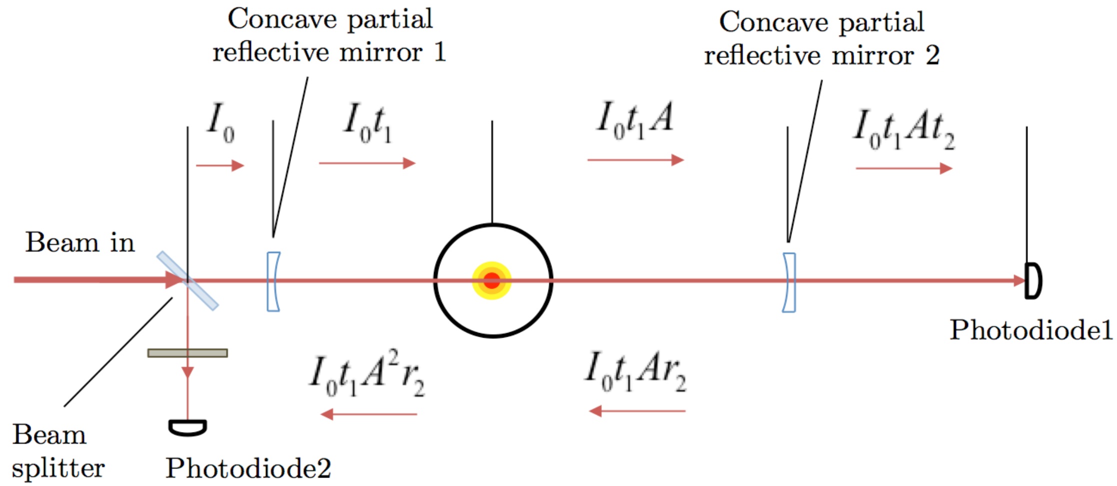
[1] Lambert J. H. Photometry, or On The Measure and Gradations of light, Color, and Shade, Augsburg, Germany. Eberhardt Klett, 1760.
[2] Beer H. W. Annalen der Physik und Chemie, 86:78 – 88, 1852.[3]
[3] A John H. Seinfeld, Spyros N. Pandis, Atmospheric chemistry and physics, 2nd edition. John Wiley and Sons, 2006.8
[4] Wang, H. Proceedings of the Combustion Institute, 33(1):41–67, 2011.

Extinction measurement

638 nm, cw, 150 mW diode laser





$$
\begin{cases}
P_t = g(\mathbf{V}, C) \\
P_t = \dfrac{I_t}{I_i} = \dfrac{A(1-R)}{1-A^2R} \\
P_0 = -\ln A = \int_{-\infty}^{+\infty} K_{ext}\,\mathrm{d}x \\
K_{ext} = \dfrac{6\pi E(m)}{\lambda} f_v
\end{cases}
$$

$\mathbf{V}$: Measured voltage sequence

C : Amplifier calibration constant

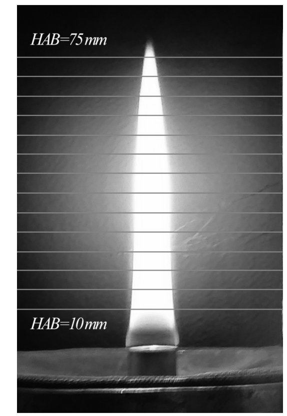
A : Attenuation ratio in one pass

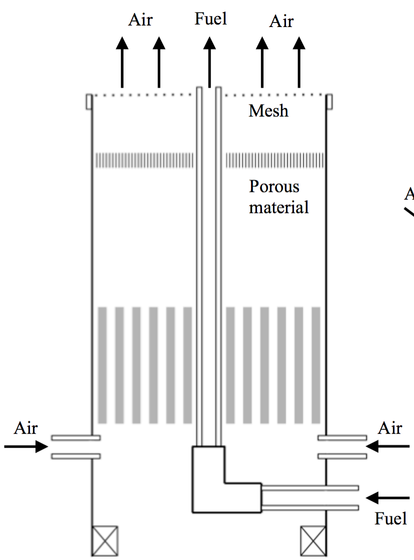
R : Product of reflectivity r_1r_2

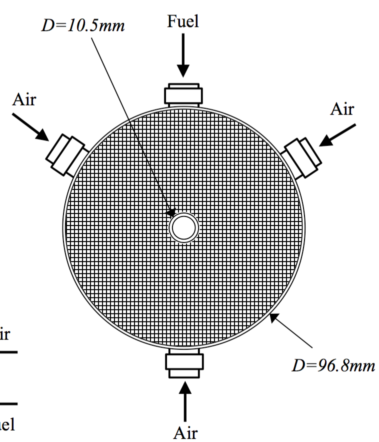
$E(m)$: Absorb function of soot

Operating conditions considered

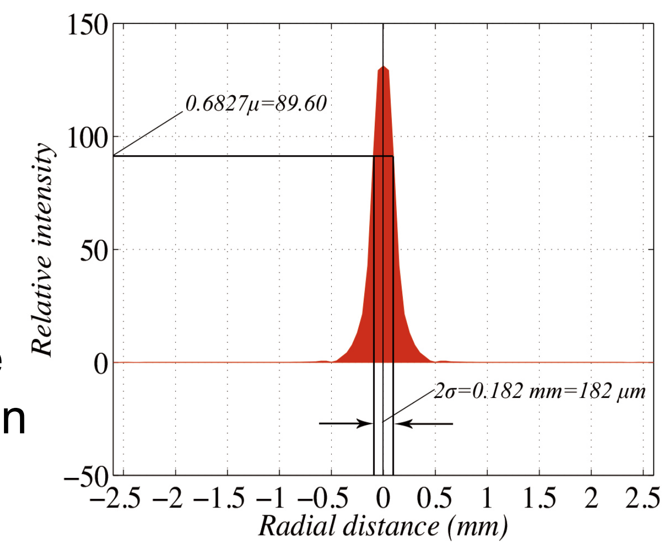
Case	CH_4(A)	CH_4(B)	C_3H_8	C_2H_4(A)	C_2H_4(B)
Inner diameter of fuel tube (mm)			10.5		
Inner diameter of air tube (mm)			96.8		
Fuel flow velocity (cm/s)	7.69	10.20	2.69	3.62	4.43
Air flow velocity (cm/s)	7.92	14.60	8.65	7.92	8.65
Fuel mass flow rate (slpm)	0.40	0.53	0.14	0.18	0.23
Air mass flow rate (slpm)	35.0	65.8	38.2	35	38.2
Visible flame height (mm)	75±2	98±2	85±2	65±2	85±2
Soot refractive index m			1.57-056i		



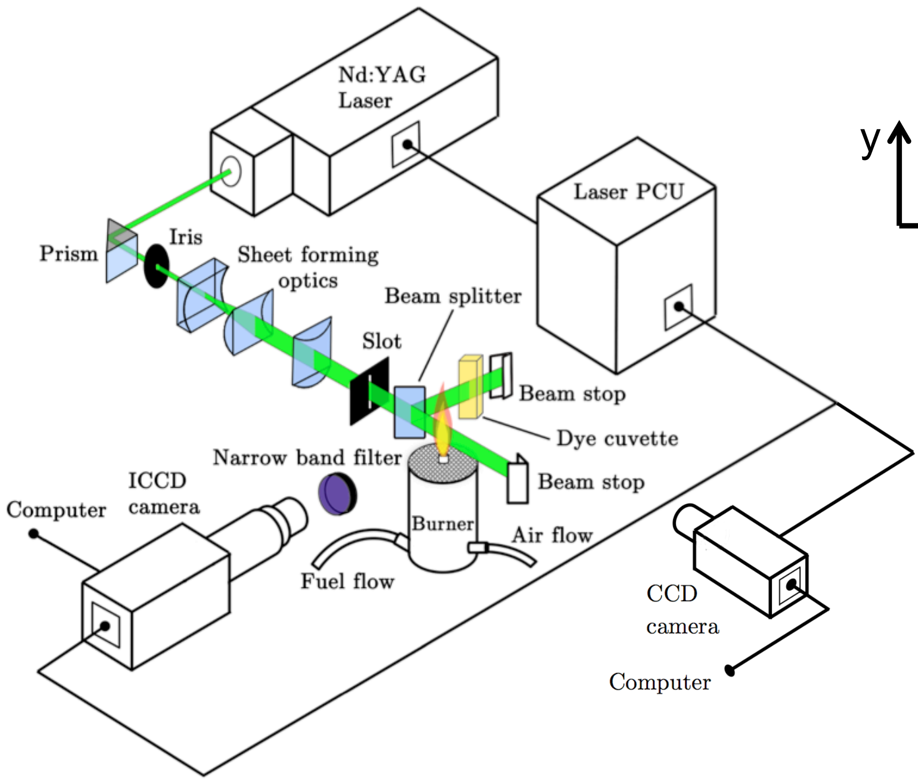


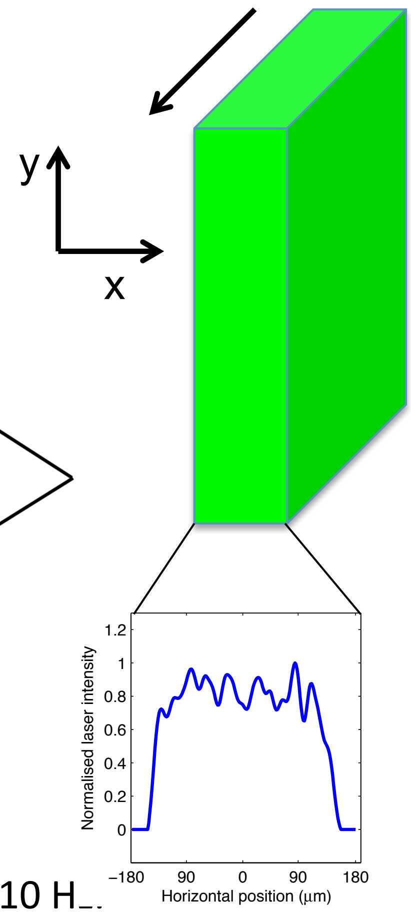


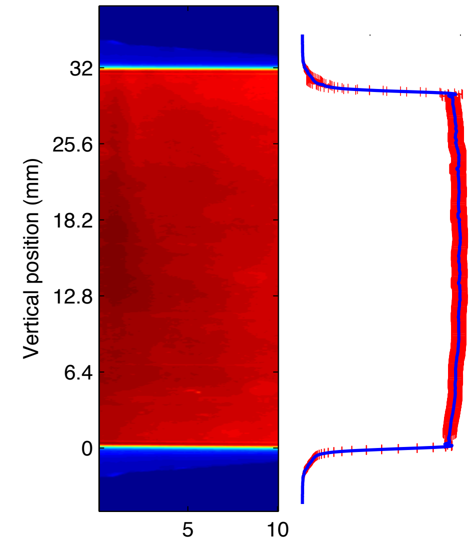
Intensity profile of the laser beam in cavity

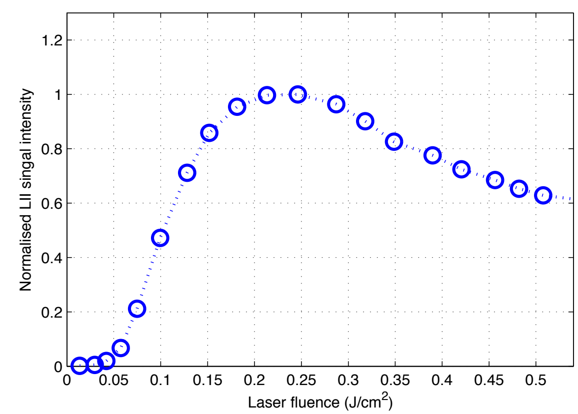


LII measurement system



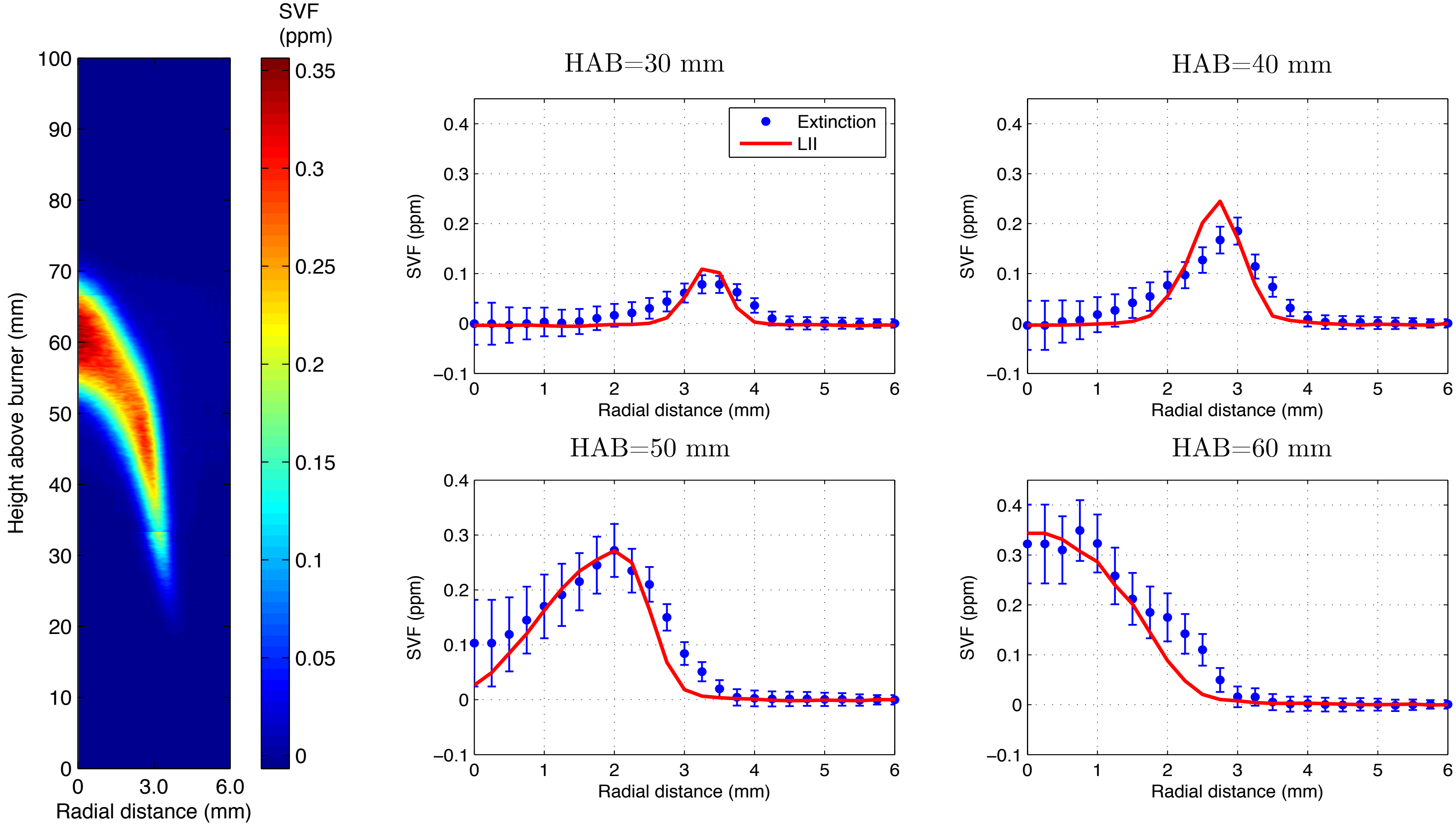




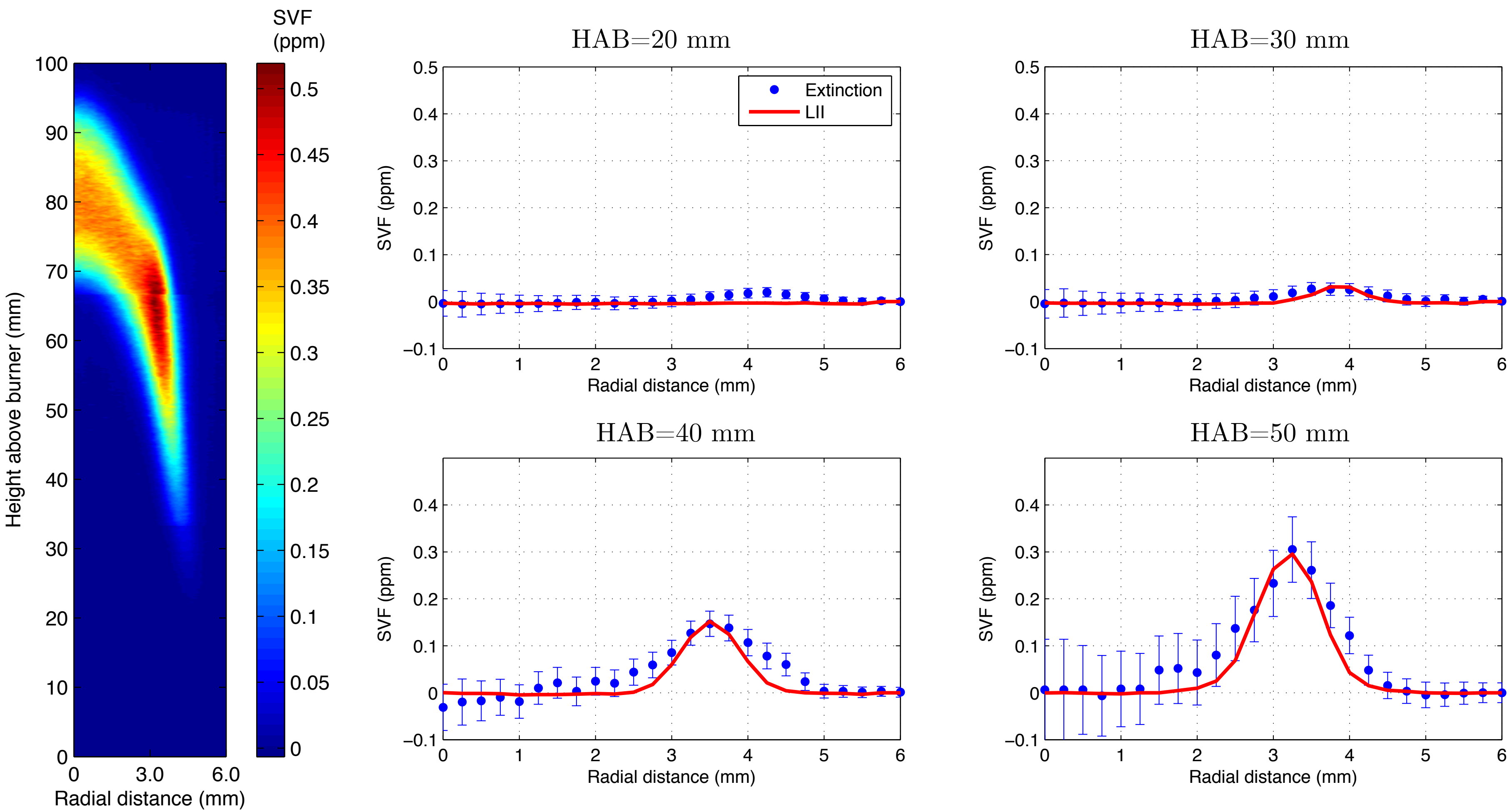


Laser: Litron Nd:YAG laser, 150mJ @ 532nm, 10 H

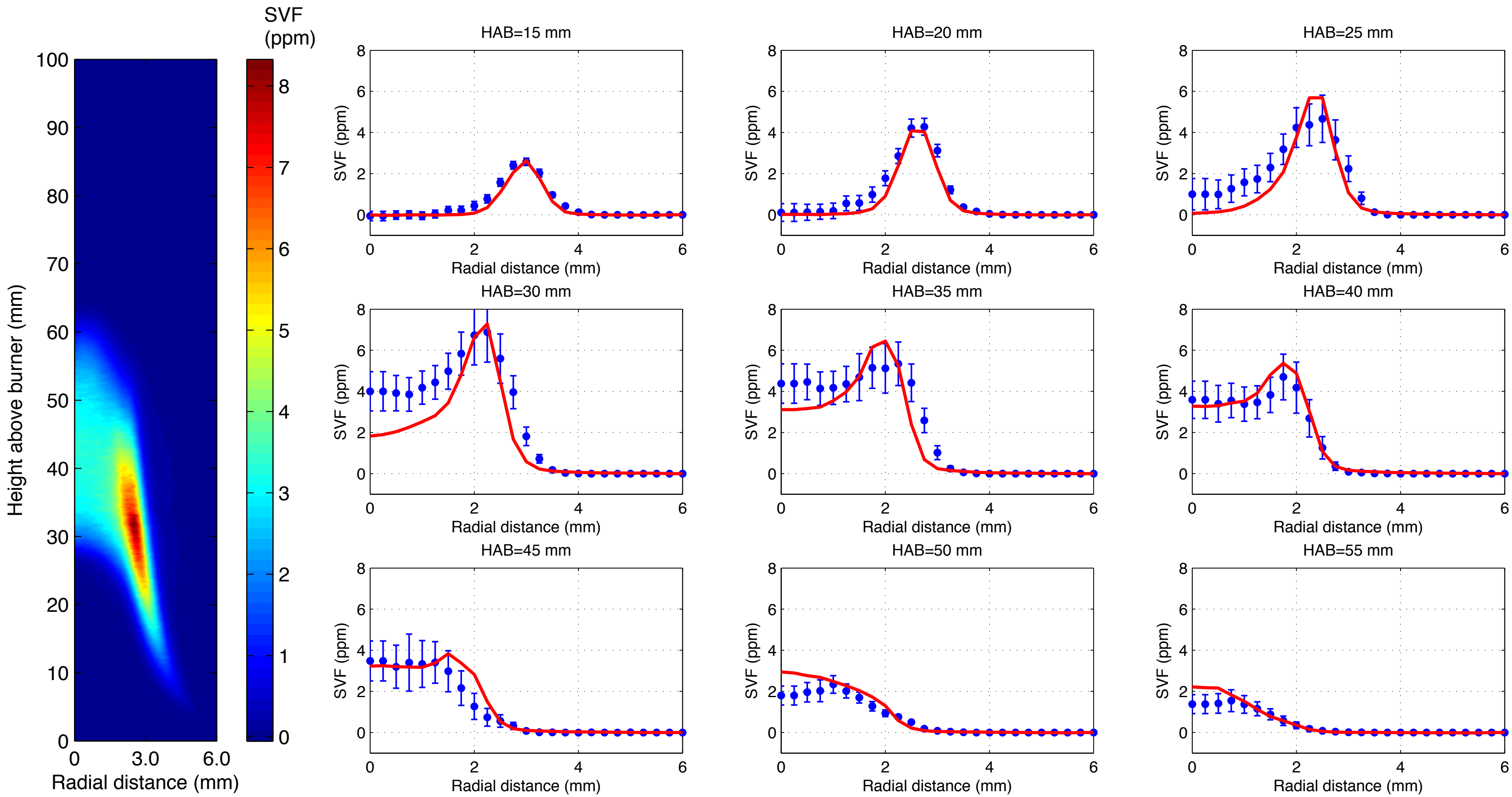
Methane flame soot volume fraction-Case A



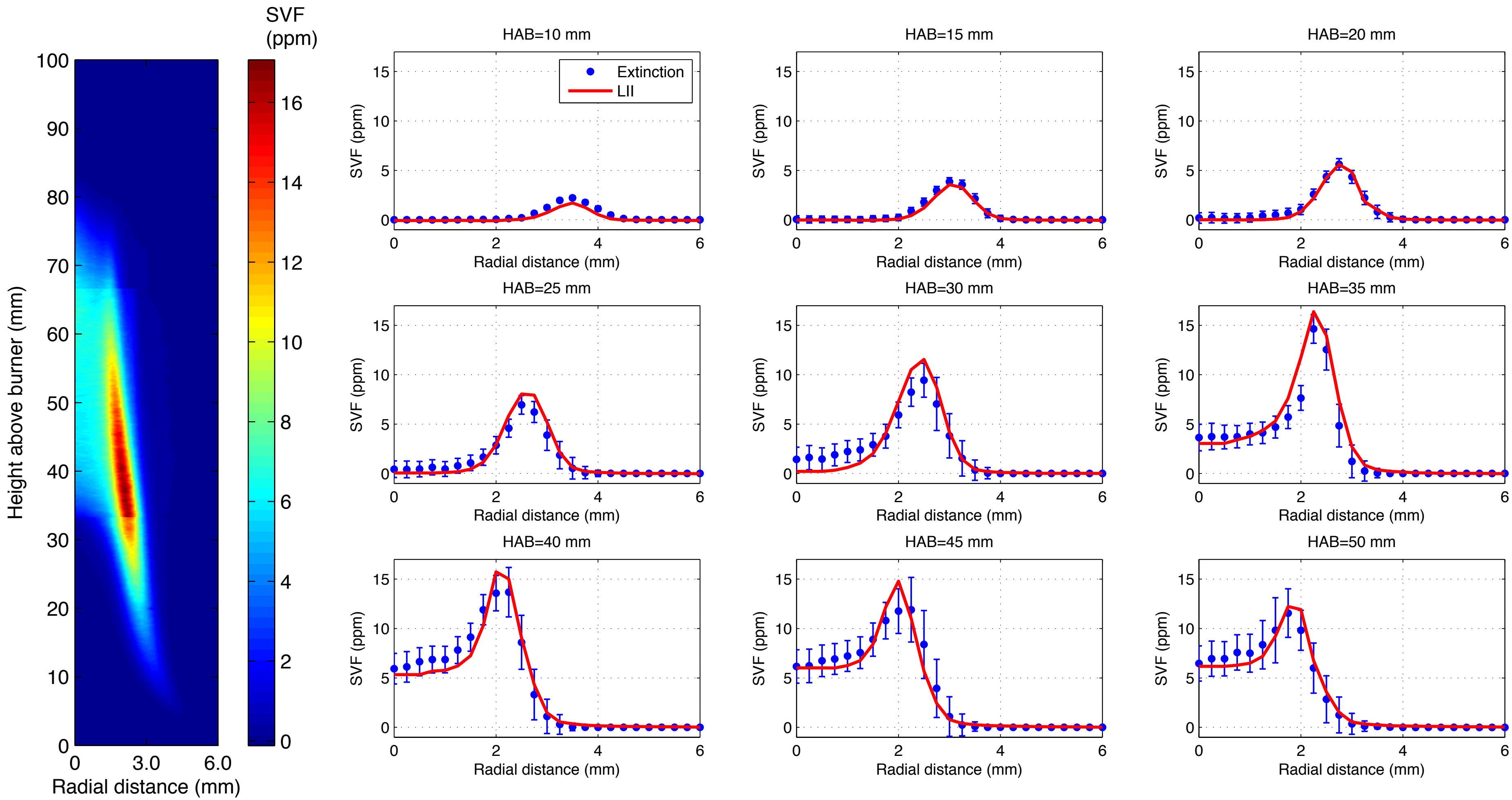
Methane flame soot volume fraction-Case B



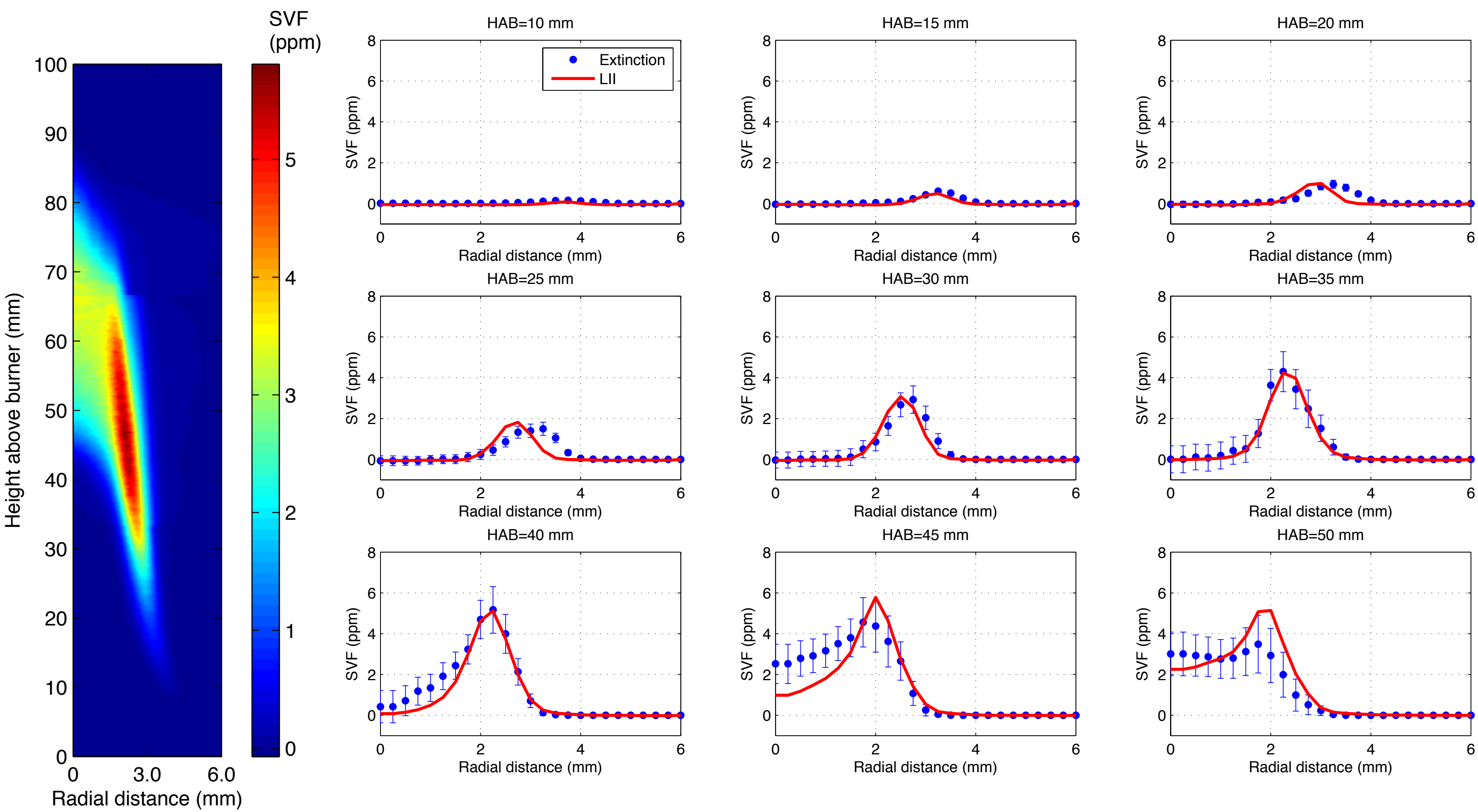
Ethylene flame soot volume fraction-Case A



Ethylene flame soot volume fraction-Case B



Propane flame soot volume fraction



Uncertainty analysis

Instrument noise

$$u_c^2(y)=\sum_{i=1}^{n}\left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i)+2\sum_{i=1}^{n-1}\sum_{j=i+1}^{n}\frac{\partial f}{\partial x_i}\frac{\partial f}{\partial x_j}u(x_i,x_j)$$

$$\mathbf{U}=u_{\mathbf{V}}=[u_{V_L};u_{V_{LF}};u_{V_F};u_{V_B};u_{V_{ref1}};u_{V_{ref2}};u_{V_{ref3}}]$$

$$u_{P_0}^2=\left(\left(\frac{\partial P_0}{\partial P_t}\right)^2,\left(\frac{\partial P_0}{\partial R}\right)^2\right)\begin{pmatrix}u_{P_t}^2\\ u_R^2\end{pmatrix}$$

$$u_{P_0}^2=\left(\left(\frac{\partial P_0}{\partial P_t}\bullet\frac{\partial P_t}{\partial \mathbf{V}}\right)^2,\left(\frac{\partial P_0}{\partial P_t}\bullet\frac{\partial P_t}{\partial C}\right)^2,\left(\frac{\partial P_0}{\partial R}\right)^2\right)\begin{pmatrix}\mathbf{U}^2\\ u_C^2\\ u_R^2\end{pmatrix}$$

$$K_{ext}=\frac{6\pi E(m)}{\lambda}f_v \quad\Longrightarrow\quad u_C(f_v)\subset[5,20]\ \text{ppb}$$

Flame fluctuation

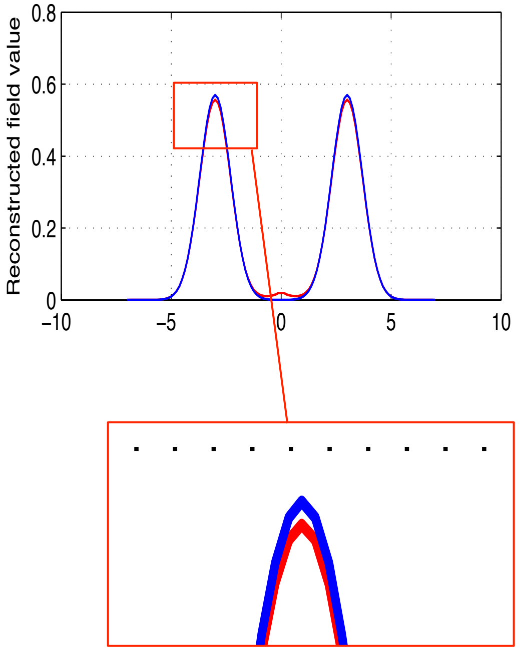
Depends on the flow field and the measuring location.

Uncertainty in *m*

Ref.	m
Dalzell *et al.* [1]	$\lambda=435.8-806.5$ nm C_2H_2: $m=1.57-0.46i$ C_3H_8: $m=1.57-0.50i$
Shaddix *et al.* [2]	$\lambda=1064$ nm C_2H_4: $m=1.7-1.0i$
Koylü *et al.* [3]	C H_4: $m=1.62+0.66i$ C_2H_4: $m=1.90+0.55i$
Kohler *et al.* [4]	C_2H_4: $m=1.60-0.59i$

$u\leq 5\%$

Uncertainties from Abel transform



$u\leq 5\%$

[1] WH Dalzell and AF Sarofim. J. Heat Transfer, 91:100–104, 1969
[2] Shaddix et al. 2011 Gordon conference on laser diagnostics in combustion, Waterwille Vally, NH
[3] Umit O. Koylu et al. In The Third International Symposium on Radiative Transfer, pages 17–21, Antalya, Turkey, 2001
[4] M. K¨ohler et al. Applied Physics B, 104(2):409–425, February 2011.

Summary

- Laser-cavity extinction is a reliable soot volume fraction measurement tool for low-soot conditions.
- Sensitivity down to 20 ppb with a spatial resolution of 200 μm.
- Can be easily applied to unsteady cases.

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Thanks!